Oscillating retreat of the last British-Irish Ice Sheet on the continental shelf offshore Galway Bay, western Ireland

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Abstract

During the Last Glacial Maximum, the British-Irish Ice Sheet extended across the continental shelf offshore of Galway Bay, western Ireland, and reached a maximum westward extent on the Porcupine Bank. New marine geophysical data, sediment cores and radiocarbon dates are used to constrain the style and timing of ice-sheet retreat across the mid to inner-shelf. Radiocarbon dated shell fragments in subglacial till on the mid-shelf constrains ice advance to after 26.4 ka BP. Initial retreat was underway before 24.4 ka BP, significantly earlier than previous reconstructions. Grounding-line retreat was accompanied by stillstands and/or

localised readvances of the grounding-line. A large composite Mid-Shelf Grounding Zone Complex marks a major grounding-line position, with the ice grounded and the margin oscillating at this position by, and probably after, 23 ka BP. The continental shelf was ice-free by 17.1 cal. ka BP, but the ice sheet may have retained a marine margin until c. 15.3 ka BP. Retreat occurred in a glacimarine setting and the ice sheet was fringed by a floating ice-shelf. Collectively, this evidence indicates a dynamic and oscillatory marine-terminating ice sheet offshore of western Ireland during the last deglaciation.

Key words: Grounding Zone Wedges; British-Irish Ice Sheet; Ice Shelf; Glacimarine; Last Glacial Maximum; Ice-Sheet Retreat; Continental Shelf

1. Introduction

Reconstructions of former ice sheets provides analogues that are useful for testing the performance of numerical ice-sheet models that seek to predict ice-sheet response(s) to climate warming. During the Last Glacial Maximum (LGM), at least 50% of the British-Irish Ice Sheet (BIIS) was marine-based (Sejrup et al., 2016). The ice sheet was drained by several large ice streams and had a marine margin extending from the west Shetland Shelf in the north (Bradwell et al., 2008; Bradwell et al 2019) to the shelf-edge of the Celtic Sea in the south (Praeg et al., 2015; Scourse et al., 2019). This broad marine margin, bordering the North Atlantic, was sensitive to both oceanographic and climatic drivers as well as sea-level change (Knutz et al., 2001, 2007; Peck et al., 2006; Scourse et al., 2009). Within the last decade, seafloor mapping of the continental shelf offshore of Ireland and Britain have provided new geomorphic evidence of the extent and style of BIIS advance and retreat (e.g., Sejrup et al., 2005, Van Landeghem et al., 2009; Benetti et al., 2010; Dunlop et al., 2011; Ó Cofaigh et al., 2012;). More recently, sedimentological and geochronological investigations have provided important constraints on

both the timing and style of BIIS retreat across the continental shelf during the last glacial cycle (e.g., Peters et al., 2015, 2016; Praeg et al., 2015; Callard et al., 2018, Ó Cofaigh et al., 2019, Roberts et al., 2018 Scourse et al., 2019).

On the Atlantic continental shelf bordering Ireland, several studies have argued that the western margin of the last BIIS terminated at the shelf edge during the LGM (e.g., Sejrup et al., 2005: Benetti et al., 2010; Dunlop et al., 2010; Ó Cofaigh et al., 2012, 2019; C. Clark et al., 2012; Peters et al., 2015, 2016; Praeg et al., 2015; Callard et al., 2018; Scourse et al., 2019). Ice rafted debris (IRD) records from deep sea cores collected along the western Atlantic margin of the BIIS imply that the ice sheet had attained a shelf-edge position by ~27 to 26.5 ka BP (Knutz et al. 2001; Peck et al. 2006; 2007; Scourse et al., 2009). Further to the north, in the Malin Sea and offshore Donegal Bay NW Ireland, this maximum position occurred after 26.8-26.3 ka, BP with onset of ice-sheet retreat between 26.7-24.8 ka BP and the majority of the shelf ice free by 23 ka BP (Callard et al., 2018; Ó Cofaigh et al., 2019). To the southwest, the Irish Sea Ice Stream reached the shelf edge between 27-24 ka BP (Praeg et al., 2015; Scourse et al., 2019) which is in line with recent dating of the maximum limit on the Isles of Scilly (Smedley et al., 2017). In the Irish Sea sector this was followed by rapid ice stream retreat by 25.1-24.2 ka (Small et al., 2018) with the ice stream margin in the northern Irish Sea Basin by 21.4 ±1.0 ka BP (Chiverrell et al., 2013; 2018). Offshore of western Ireland, Peters et al. (2015, 2016) proposed an ice lobe that extended across Galway Bay and formed the western-most extent of the last BIIS, with geomorphic evidence of grounded ice out on the Porcupine Bank (Fig. 1), some 200 km from the Irish mainland. Peters et al. (2016) dated this advance to sometime after 24.1 ka BP and proposed late retreat of ice from the shelf with ice still grounded on the Porcupine Bank as late as 21.8 ka BP and only reaching the mid-shelf by 18.5 ka BP. This contrasts with results on the timing of ice sheet retreat from elsewhere along the western margin

(see above) and warrants further investigation to determine the relative importance of external vs. internal controls on the mechanisms behind the rapid retreat of marine-terminating ice sheets.

This paper presents new marine geophysical, sedimentological and geochronological data to reconstruct the pattern and timing of grounded ice on the mid-shelf between Galway Bay and the Porcupine Bank, offshore of western Ireland (Fig. 1). The objectives are to: 1) describe and characterise the glacial geomorphology on the mid and inner-shelf offshore Galway Bay, 2) to determine the nature of the depositional environments and style of ice sheet retreat, and 3) to provide a better-constrained retreat history for this sector of the British-Irish Ice Sheet across the mid to inner shelf.

2. Regional setting.

The study area lies offshore of counties Clare and Galway, central western Ireland and is confined to the shallow (<200m) mid to inner-shelf and the adjacent 0.5º slope of the Slyne Trough that forms a depression in the mid-shelf sea-floor (Fig. 1). This portion of the shelf extends and widens for up to 150 km westwards from the Irish coastline. Seismic reflection profiles show that the inner shelf is underlain by an offshore extension of the Precambrian metasedimentary rocks of Connemara and the Carboniferous limestone of the Clare Basin (Naylor et al., 1999) that lie close to, and crop out at, the seabed. Pliocene and Quaternary sediments overlie these basement bedrocks. The relatively flat sea-floor of the inner and mid-shelf is disrupted in the west by the Slyne Trough. This trough forms a gently sloping, 70 km wide depression in the mid-shelf. Seismic profiles of the eastern edge of the Slyne Trough, reveal a thick (160 m) sequence of Pliocene and Pleistocene sediments which are described as a proglacial fan by McCarron et al. (2018) (see below for more detail). The Slyne Trough

reaches depths of ~300 m bsl (below sea level) and links the mid-shelf to the Porcupine Bank on the outer-shelf. Porcupine Bank is a shallow, shelf-edge bank rising to a minimum of 145 m bsl, located 200 km due west of Ireland and is bounded to the north and west by the outer-shelf break at ~400 m bsl.

2.1. Glacial history

During the LGM the Irish Ice Sheet extended from the central Irish Midlands, Kerry-Cork Mountains and Connemara Mountains and converged in and across Galway Bay (Greenwood and Clark, 2009; Ballantyne and Ó Cofaigh., 2016). The offshore record of this sector of the BIIS has, until recently, been poorly constrained and our understanding has been reliant upon IRD records from deep sea cores collected south of the study site (core MD01-2461 Fig. 1; Peck et al 2006, 2007) and from the Donegal-Barra Fan to the north (e.g., Knutz et al 2001; Fig. 1). These IRD records imply that the BIIS had extended onto the continental shelf by 29 ka BP, and reached the shelf-edge by 27 to 26.5 ka BP. The IRD record from core MD01-2461 (Fig. 1) contains a constant, but variable, IRD flux between 26.5-17 ka BP, indicating both a persistent calving front but also evidence of destabilisation and readjustment of the marine margin throughout this period (Peck et al., 2006).

A number of recent marine geological and geophysical investigations on the continental shelf offshore western Ireland have extended our understanding of the glacial history of this region. On the Porcupine Bank (Fig. 1), Peters et al. (2015, 2016) mapped and dated a number of grounding-zone wedges (GZWs) on the basis of which they argued that grounded ice was positioned at the shelf edge as late as 25-24 ka BP with initial ice advance prior to this date. Inshore of the Porcupine Bank a large arcuate sediment ridge marks the mid-shelf grounding-line position (Fig. 1). This feature, termed the ‘Galway Lobe Grounding Zone Wedge’ by

Peters et al. (2015, 2016) (but referred to as the 'Mid-Shelf Grounding Zone Complex' in this study) was dated by Peters et al. (2015, 2016) who concluded that it marks a grounded ice margin dating to c. 21.2-18.5 ka BP. Further to the east, a second smaller sediment ridge marks a grounded ice margin on the mid-shelf at 18.5 ka BP with ice retreating inshore after this time (Fig 1). Based on these dates, Peters et al. (2016) concluded that retreat across the inner-mid shelf was rapid. In contrast, McCarron et al. (2018) argued that grounded ice did not extend onto the Porcupine Bank during the LGM, but rather was restricted to the 200 m isobath on the mid-shelf. The evidence for this is a thick sedimentary fan (termed the 'Connemara Fan' by McCarron et al., 2018) that lies seaward of this position and extends down into the Slyne Trough. Sub-bottom seismic data from the fan shows a series of stacked sediment layers that were likely deposited during multiple periods of ice occupancy of this grounding line position (see McCarron et al., 2018).

3. Methodology

Cruise JC106 of the *RRS* James Cook in August 2014 collected sub-bottom profiler (chirp) data and sediment cores (Fig. 1). The SBP120 chirp sub-bottom profiler is installed as an extension of the EM120 multibeam system, with frequency limits between 2.5 – 7 kHz and a maximum depth resolution of 0.3 ms. SBP profiles were visualised and interpreted using the IHS Kingdom™ software. To convert the two-way travel time to depth estimates in the sub-bottom profile data, we applied an average sound velocity of 1600 m s^{-1} through marine sediments.

Eighteen vibrocores were retrieved (Table 1) using a British Geological Survey vibrocorer with a 6 m barrel and 8 cm core diameter. A further three piston cores up to 7.7 m long were taken from the inner shelf within 15 km of the Connemara coast using a UK National Oceanography Centre piston corer with a 12 cm diameter barrel. The underwater position of each core was

recorded using a Sonardyne Ranger USBL beacon attached to the corer. The on-board GEOTEK MSCL measured gamma density and magnetic susceptibility of each core at two centimetre resolution prior to splitting (results for each core are shown in Supplementary Information Figures 6 to 8). Shear vane measurements were made on the split core surface using a hand-held Torvane at 10 cm intervals. A GEOTEK XCT scanner provided X-radiographs on the split cores at a 92 μm resolution to further refine the core lithofacies. The X-radiographs, visual logs and physical properties were used to identify seven lithofacies (LF1-LF7).

From the cores a mixture of paired bivalves, mixed benthic foraminifera samples and shell fragments were collected and cleaned for radiocarbon dating. It is assumed that all dated material lived in a benthic and marine environment. Only whole, unabraded foraminifera specimens were picked from sieve (500, 180 and 63 μm) residues, with the assemblage dominated by the cold-water species *Elphidium clavatum*, *Cassidulina reniforme*, *Nonionella labradorica* and *Cibicides lobatulus.* Seventeen samples for radiocarbon dating (Table 2) were collected from cores on the shelf and mid-shelf slope of the Slyne Trough and submitted to the NERC Radiocarbon Facility for dating (SUERC publication codes) or the Keck C Cycle AMS laboratory, University of California, Irvine (UCIAMS publication codes) for ^{14}C dating. The primary aim of the dating was to constrain the timing of ice-sheet advance and retreat across the shelf. Our dating strategy was therefore threefold: (1) we dated reworked shell fragments in overconsolidated diamictons interpreted as subglacial tills to provide a maximum age on till formation and thus ice sheet advance; (2) we dated mixed benthic foraminifera samples and shell fragments from glacitectonised glacimarine sediments. These dates constrain the timing of initial glacimarine deposition and thus ice sheet retreat, but they also provide a maximum age for the subsequent glacitectonism and grounding-line oscillation/readvance; (3) we dated

shell and foraminiferal samples from deglacial glacimarine sediments to constrain the timing of ice sheet retreat. These samples were taken from as close to the transition with underlying subglacial sediments as possible or, where cores bottomed out in glacimarine sediments, we took the sample from as close as possible to the base of the core. The stratigraphic positions of the dates are shown and are discussed in context with the lithofacies interpretations (see Fig. 3, 6 and 8)

The conventional ^{14}C ages were calibrated using the Marine13 calibration curve with an inbuilt marine reservoir correction of 400 years and a ΔR of 0 years (Oxcal; Reimer et al., 2013). The ages are reported in the text as the calibrated 2σ median results (see Table 2). It is likely the samples would be subject to large and variable local ΔR during the LGM and late glacial period (e.g., Austin et al., 1995; Peck et al., 2006; Singarayer et al., 2008). We have applied two further age calibrations using the ΔR +300 and +700 yrs (c.f., Small et al., 2013; Table 2) as a sensitivity test. However, the different ΔR values has a modest impact and due to uncertainties in the correct reservoir age for this time period (Wanamaker et al., 2012) we have kept the ΔR of 0 in the text whilst acknowledging the caveat this could be significantly more.

4. Results and Interpretation

4.1. Acoustic Profiles

We present three acoustic profiles from the study area describing the major morphological features and acoustic signature of each. Where cores are available we also include brief reference to the associated sedimentary characteristics and we present full sedimentological descriptions in section 4.2.

4.1.1. Mid-inner shelf lines - description

Two acoustic profiles extend 150 km from the inner shelf westwards to water depths of 95-320 m. The northern profile from 0-39 km is characterised by a low gradient slope extending down into the Slyne Trough with a high amplitude seafloor reflector that is locally grooved (e.g., from 5-10 km and 16-22 km, Fig. 3a). The acoustic return beneath the seafloor appears to be relatively weak. Occasional point source reflectors are visible (e.g., at ~25 km). The sediments become more diffusely stratified with distance westwards and downslope (between 0-17 km). The slope is interrupted by a prominent topographic high between 18-22 km (Fig. 2a, 3a). Cores from this topographic high recovered predominantly massive pebbly mud (195VC and 196VC, Fig.3b), whereas a core from further upslope in 240 m water depth recovered clast-poor, laminated mud (194VC) (see section 4.2).

From 39 km westwards the seismic profile is characterised by a series of low relief and broad mounds (annotated as "M" in Figs. 2 and 4), at the seafloor. The eastern most mound (M1) at 39-72 km (Fig. 2a), is a multi-crested composite feature. Internally M1 is acoustically homogeneous. A core from this location recovered stiff, massive, matrix-supported diamicton overlain by bedded gravel and sand (193VC). To the east, these mounds transition into a series of 22 ridges that have a shorter wavelength (Fig. 4a) and are 5-9 m high and on average 720 m wide. These smaller ridges extend eastwards and beneath mound M2 (Fig. 2a, 4a). M2 (86.5-104 km; Fig. 2a, 4a) has a pronounced wedge-shaped geometry and is 23 m thick. M3 extends from 118-134 km (Fig. 2a) and shows some steeply dipping sub-seafloor reflectors. The final mound along the northern profile is M4 (Fig. 2a, 4c), which occurs from 132-136 km (Fig. 2a), is at least 19 m high and appears to be predominantly acoustically transparent.

Along the profile, acoustically stratified sediments infill small basins between the mounds described above (Fig. 2a, 4a). Stratification in these infills is variable, and up to 27 m thick.

The most prominent infill F1, occurs between mounds M1 and M2 from 73-90 km on the profile, and onlaps both mounds (Fig. 2a, 4a). The lower half of the infill is acoustically transparent and undulating, broadly conformable to the underlying smaller ridges (see above). The infill becomes more stratified in the upper half. Stratification ranges from locally well-developed but contorted in the deeper and central part of the basin fill, to more diffuse elsewhere. At the eastern end of the F1 basin the acoustic stratification is interrupted by a lens of predominantly transparent sediment. Faint internal reflectors are visible in places and the lens is attenuated along profile to the west. Infill F2 occurs to the east of M2 and comprises 11 m of acoustically homogeneous sediment with, in places, faint internal reflectors. At the eastern end of the profile (Fig. 2a, 4c) mound M4 is on-lapped to the west by hummocky-contorted sediment (F3) which pinches out westwards. M4 is onlapped to the east by a basin fill of acoustically stratified sediment 25 m thick with parallel internal reflectors (F4). Stratification varies vertically from more continuous and well laminated to diffuse. A series of cores from these basin fills recovered contorted, laminated silty muds (cores 191VC, 190VC, 189VC, 188VC and 186VC; Fig. 6) (see section 4.2).

The southern profile contains a series of mounds (M1 and M5-M7) extending west to east across the shelf (Fig. 2b). The outermost mound M1 extends from 40-77 km, is multi-crested, and 7-21 m high. This multicrested feature is a continuation of M1 identified in Figs. 2a and 4a and hence also named M1 in Figs. 2b and 5a. Cores from this mound comprised bedded sand and gravel apart from 211VC, which recovered almost 2 m of massive diamicton (Fig. 6). A series of buried, low amplitude ridges extend from 76-102 km and similar features are present within M1 from 66-71 km (Fig. 2b, 5). At 102 km the reflector, which defines these buried ridges, rises to the seabed. From 102-116 km eastwards there are a series of irregular, undulating sub-bottom reflectors. These are overlain by mound M5. The eastern end of the

profile from 117-147 km is characterised by three well developed low amplitude mounds (M5-M7) which range from 10-19 m high and 5-13 km wide (Fig. 2b). M6 and M7 are internally homogeneous; M5 shows some faint, sub-horizontal internal reflections towards its western end.

As in the northern profile, acoustically stratified basin fills occur between several mounds (Fig. 2b). A basin fill occurs between 72 and 92 km, and it is ~7 m thick. Internally this is predominantly acoustically stratified, however, locally it contains discrete lenses of acoustically transparent sediment (Fig. 2b, 5). Towards the eastern end of the profile, a basin fill up to 5 m thick onlaps M6 and M7.

4.1.2. Mid-inner shelf lines – interpretation

Both mid-inner shelf acoustic profiles are characterised by a series of mounds separated by basin fills of variably stratified sediment. The mounds are low amplitude features but are typically wide (3 –15 km) and some have a distinct wedge-shaped geometry with their base defined by a sub-bottom reflector (e.g., M2 and M5). Internally they are predominantly acoustically homogeneous although in the case of M5 diffuse stratification is visible. These characteristics are consistent with an interpretation of the mounds as grounding-zone features formed during ice-sheet retreat. The distinct wedge-like geometry in some cases is consistent with grounding-zone wedges (GZWs) described from the literature **(**cf. Batchelor and Dowdeswell, 2015). The steeply dipping reflectors on M3 on the northern profile may record sediment progradation at the grounding-line or could alternatively reflect, at least in part, the presence of bedrock close to the seafloor. On both acoustic profiles, the outermost mound (M1) is multi-crested suggesting the grounding-line was oscillating on the outer shelf.

The low amplitude buried ridges on the outer shelf (see section 4.1 above) are present on both profiles and are an order of magnitude smaller than the bracketing larger GZWs (M1/M2 and M1/M5). Their dimensions are inconsistent with an origin as De Geer Moraines (cf. Todd et al., 2007). We interpret these ridges as recessional features formed by stillstands and/or minor oscillations of the grounding line during ice-sheet retreat (Shipp et al., 2002; Ó Cofaigh et al., 2012).

The acoustically stratified basin fills that occur between the mounds reflect sediment progradation beyond the grounding-line, most likely by a range of glacimarine processes including sediment gravity flows, iceberg rafting and suspension settling from turbid meltwater plumes (Hogan et al., 2012, 2016). However, in some basins (F1 and F3) the sub-bottom reflectors are contorted and sediment cores from F1 recovered deformed, laminated muds. We suggest that this represents glacitectonism by grounded ice and provides further support for an oscillatory grounding line on the outer shelf. The transparent sediment lens at the eastern end of the F1 basin may be a debris flow sourced from the distal face of the GZW of M2 (c.f. Dowdeswell et al., 2010; Batchelor et al. 2011). However, it both rises and is attenuated westwards suggesting an alternative interpretation as a glacitectonic sediment raft (Evans, 2018). The distribution of mounds separated by stratified glacimarine basin fills across the shelf indicates ice sheet retreat was episodic with occasional pauses and GZW/basin fill formation.

West of the outermost GZW (M1, Fig 1a and 3a) the slope extending down into the Slyne Trough exhibits diffuse acoustic stratification. This suggests sediment progradation into deeper water from a grounding line which delivered glacigenic material downslope, most likely by sediment gravity flow processes (e.g. King et al., 1996; Stravers and Powell, 1997). However, the thick laminated mud sequences recovered in core 194VC implies deposition also involved

meltwater delivery. The seafloor incisions are consistent with iceberg scouring (Sacchetti et al., 2015; Thébaudeau et al., 2016).

4.1.3. Inner shelf offshore Connemara - description

A third sub-bottom profile, ~23.5 km in length and orientated SE-NW, was collected from 15 km offshore of the Connemara coast. The acoustic basement visible in the profile is regionally extensive and high amplitude (Fig. 7). It forms an irregular topography characterised by a series of highs, that crop out at the sea bed and intervening basins some of which contain sediment infills between 4-14 m thick (see below).

The basin infills are characterised by two distinct acoustic facies, which have a consistent vertical arrangement along the profile. The lower acoustic facies reaches up to 10 m thick and internally is variably acoustically stratified ranging from continuous horizontally layered sediments within the basins (e.g., location of core 184PC in Fig.7b), to contorted, disrupted and discontinuous internal reflectors (e.g., location of core 181VC in Fig. 7b). This unit was captured in four cores (180PC, 181VC, 183VC, 184PC) and comprises silty clay and clayey silt that is variably laminated-contorted (see section 4.2). The upper boundary of this acoustic facies is smooth to undulating and of medium to high strength. Where sampled this boundary comprises matrix-supported, poorly sorted, sandy gravel with abundant shell fragments.

The basin fills are capped by a well-developed, prominent acoustically transparent facies (Fig. 7). This reaches a maximum thickness of 11 m in the deepest basins. Cores from this facies recovered well sorted, saturated, silty sand that is massive and bioturbated. Its upper boundary is marked by a high amplitude, smooth reflector, which often forms the seafloor (Fig. 7).

4.1.4. Inner shelf offshore Connemara - interpretation

The acoustic basement visible in the profile is interpreted as bedrock on account of its high amplitude, distribution (both cropping out at seafloor and underlying stratified basin fills) and irregular form. The basin fills are consistent with formation in deglacial and postglacial environments. The lower acoustically stratified facies consist of laminated to contorted muds and is interpreted as a product of glacimarine sedimentation during ice sheet retreat (cf. Ó Cofaigh et al., 2016). These types of sediment are often produced by the rain-out of fine-grained sediment from suspension alternating with sediment gravity flow processes. Contorted bedding most likely reflects high sedimentation rates and the irregular topography that would have facilitated downslope resedimentation of fine-grained meltwater deposits (Hogan et al., 2012).

These glacimarine sediments are separated from the overlying acoustically transparent facies by poorly-sorted sandy gravel with abundant shells, which is interpreted as a lag deposit associated with bottom current reworking (Vianna et al., 1988). The overlying transparent facies comprises well sorted, saturated silty sands and are suggestive of a more quiescent depositional setting, most likely postglacial (Cooper et al., 2002).

4.2. Lithofacies descriptions

A total of twenty-one cores, three piston cores and eighteen vibrocores, were collected offshore of the Connemara coastline and across the slope and mid-shelf of Galway Bay. From these cores, we identify seven lithofacies (LF1-7) and describe these below.

4.2.1. LF1: Massive diamicton (Dmm) and minor stratified diamicton (minor Dms)

LF1 predominantly comprises massive, matrix-supported diamicton (Dmm). It is the basal lithofacies in six cores; two from the mid-shelf slope (195VC and 196VC, Fig. 3), three

(193VC, 187VC and 211VC Fig. 6) from the tops of the mid-shelf grounding-zone wedges (see section 4.1) and one from the inner shelf offshore of Connemara (181VC, Fig. 8). In core 191VC from a mid-shelf stratified basin fill, LF1 overlies laminated mud (LF2 and LF3).

In cores 195VC and 196VC from the mid-shelf slope LF1 is a dark grey (10YR 4/1), matrix-supported diamicton, with clay-silt matrix that contains abundant subrounded gravel to pebble-sized clasts. In 196VC LF1 is predominantly massive. Shear strengths in this core are 20-50 kPa increasing downcore (Fig. 3). In core 195VC, LF1 is also massive below 250 cm depth and shear strength values are generally greater than 60 kPa and reaching a maximum of 108 kPa at the base of the core. Above 250 cm depth in 195VC, however, LF1 ranges from massive to, locally, diffusely stratified. The diffuse stratification is localised, only visible in the x-radiographs and is imparted by sub-horizontal grain alignments and subtle textural variation (Fig. 9b, Supplementary Information Fig. 3). The shear strength of LF1 above 250 cm depth in this core is generally less than 30 kPa with a minimum of 10 kPa. Clast abundance of LF1 in cores 195VC and 196VC is variable. It is noticeably higher in 196VC (see x-ray Fig. 9a and Supplementary Information Fig. 3 and 4 for comparisons). The physical properties of Dmm in core 195VC and 196VC show a medium wet bulk density and magnetic susceptibility averaging 2.03 gr/mm and 104.3 $x10^{-5}$ SI respectively (see Supplementary Information for details).

Shell and coral fragments, and foraminifera are abundant throughout cores 195VC and 196VC. Radiocarbon dates on five shell fragments, four from 195VC and one from 196VC, constrain the age of LF1 (Table 2, Fig. 3). In core 195VC, three dates were obtained from the massive, stiff diamicton below 250 cm depth. A sample from 309-310 cm was beyond the range of radiocarbon dating but two further samples provided ages of 32994 ± 439 cal BP (SUERC-

60169) and 32407 ± 561 cal BP (SUERC-60168). A fourth sample at 219 cm depth from the softer massive to diffusely stratified diamicton dated 22849 ± 231 cal BP (SUERC-60165) (Table 2, Fig. 3). Finally, a shell fragment from 145-147 cm in core 196VC dated 15349 ± 204 cal BP (SUERC-60170).

In the mid-shelf cores and offshore Connemara, LF1 is a massive, matrix-supported diamicton with a clay-silt matrix. It is poorly sorted containing abundant gravel to granule-sized clasts including sub-rounded pebbles reaching up to 4 cm in diameter. The matrix is dark grey (5Y 4/1), predominantly massive, and contains occasional sandy pods and shell fragments. However, in core 211VC the matrix exhibits a gradational colour change downcore from dark grey (7.5 YR 4/2) to very dark grey (7.5 YR 4/1) and there is marked textural variation imparted by more clast-rich/gravelly zones. In core 191VC, LF1 is underlain by 27 cm of laminated mud (LF2) which becomes progressively more deformed (LF3) up-core forming a mixed or 'amalgamation zone' with LF1 (Fig. 9c, Supplementary Information Fig. 1). The upper boundary between LF1 and the overlying laminated mud of LF2 is sharp and the laminations are well preserved (Fig. 9d, Supplementary Information Fig. 1). In these mid-shelf cores, LF1 is very stiff with shear strength values ranging from 87 to 200 kPa. Overall, LF1 from the mid-outer shelf has a high wet bulk density and magnetic susceptibility averaging 2.15 gm/cc and 163.1 $x10^{-5}$ SI respectively (see Supplementary Information for details).

Four radiocarbon dates were obtained from LF1 on the mid-shelf. A shell fragment from 177 cm depth in core 191VC returned a non-finite age. The oldest age, from core 193VC is 26,446 ± 284 cal BP (SUERC-60164). A further two ages collected from core 211VC are 20,957 ± 210 cal BP (SUERC-60158) and 17,319 ± 192 cal BP (SUERC-60179) respectively.

400 *4.2.2. LF2: Laminated mud (Fl)*

401 LF2, laminated mud, occurs in six cores and consists of laminated clast-poor mud. In cores
402 180PC, 183VC and 184PC (Fig. 8) from offshore of Connemara on the inner shelf, LF2 forms
403 the basal lithofacies; in core 181VC, LF2 overlies Dmm (LF1). It comprises the basal
404 lithofacies in core 194VC (Fig. 3) from the mid-slope and also occurs in 191VC (Fig. 6) where
405 it is interbedded with LF3 (Fl (def)) and LF1 (Dmm). LF2 comprises dark grey to very dark
406 grey (5Y 3/1, 5Y 4/1) alternating horizontally laminated silts and clays. Individual laminae
407 range from mm-cm thick. The upper and lower contacts vary from sharp, to diffuse and
408 undulating. In some instances, the laminae have a wispy appearance (e.g., core 181VC, Fig.
409 9e). In core 184PC individual laminae become thicker and more diffuse up core. LF2 is
410 predominantly clast free but locally may contain gravel- to granule-sized clasts that lie in
411 discreet horizons (e.g., core 184PC Fig. 9h), or as occasional isolated pebbles (e.g., core 194VC
412 Supplementary Information. Fig 2). Whole bivalves, abundant shell fragments and
413 foraminifera are present throughout. Bioturbation is visible as burrows in the x-radiographs
414 and as black mottles in core section but declines in frequency with depth downcore. Shear
415 strengths in LF2 are variable. In core 194VC from the mid-slope LF2 is stiff, exhibiting shear
416 strengths of 50-150 kPa. In core 191VC shear strengths of LF2 range from 60-90 kPa. This
417 contrasts with cores from the inner shelf offshore Connemara where shear strengths measured
418 in LF2 are much lower at 10-20 kPa. Wet bulk density is comparatively low, averaging 1.99
419 gm/cc whilst magnetic susceptibility is higher averaging 184.9 $x10^{-5}$ SI. However, when
420 comparisons are made between areas, the average magnetic susceptibility is much higher from
421 cores collected from offshore Connemara (180PC, 181VC, 183VC and 184VC) compared to
422 the Fl captured on the mid-shelf (191VC and 194VC) with values averaging 260.6 $x10^{-5}$ SI and
423 75.9 $x10^{-5}$ SI respectively. This likely reflects a textural difference with the Connemara cores,

424 which lie close to the present-day shoreline, and have an increased sandy component compared
425 to the mid-shelf cores (see Supplementary Information for details).
426
427 A sample of mixed benthic foraminifera from the base of 194VC dated 24361 ± 202 cal BP
428 (SUERC-58323). A further three radiocarbon dates were obtained from samples from the bases
429 of cores 180PC and 184PC. A sample of mixed benthic foraminifera from 180PC yielded a
430 calibrated age of 16,962 ± 214 cal BP (SUERC-63562) while two articulated bivalves from the
431 base of 184PC dated 17,101 ± 270 cal BP (UCAIMS-186921) and 17,101 ± 247 cal BP
432 (UCAIMS-186924) respectively.
433
434 *4.2.3. LF3: Deformed laminated mud (Fl (def))*
435 LF3 comprises deformed laminated mud. It was recovered in seven cores from the slope
436 (194VC, Fig. 3) and mid-shelf (186VC, 188VC, 189VC, 190VC, 191VC and 212VC, Fig. 6),
437 and two cores from offshore Connemara (180PC and 184PC, Fig. 8). LF3 is a heavily deformed
438 laminated mud (Fl (def)) that varies in nature spatially. In core 194VC Fl (def) is a stiff (24-56
439 kPa) colour mottled, silty clay and clayey silt containing water escape structures in the form of
440 ball and pillow features that are visible in x-ray (Fig. 9g, Supplementary Information Fig. 2).
441 Whole bivalves, shell fragments and foraminifera are present throughout as well as occasional
442 small gravel-sized clasts. In core 194VC the deformed laminated mud of LF3 gradationally
443 overlies the laminated mud of LF2.
444
445 Across the mid-shelf, Fl (def) is only recovered in cores from the basin infills and it forms the
446 basal lithofacies of these cores. Here LF3 comprises a heavily deformed (e.g., 189VC, Fig. 9f),
447 laminated fine sand and silty clay. Individual laminae/layers range from mm to 2 cm in
448 thickness. The laminae have blurred upper and lower boundaries. The matrix varies in colour

with the fine sand units being black (5YR 2.5/2) and the silty clays being dark grey (10YR 4/1). In these mid-shelf cores, LF3 ranges from firm to stiff with shear strengths that range from a minimum of 17 kPa (core 190VC) to 88 kPa (Core 191VC). The wet bulk density for LF3 across the mid-shelf and Slyne Trough is high, averaging 2.11 gm/cc whilst magnetic susceptibility is medium averaging 131.8 $x10^{-5}$ SI (see Supplementary Information for details).

Three radiocarbon dates were obtained from LF3 in core 190VC. The dates are in reverse stratigraphic order (oldest at the top) and are 22,964 ± 329 cal BP (UCIAMS-164434) (192-194 cm), 25,414 ± 241 cal BP (UCIAMS-176384) (180-182 cm) and 27,267 ± 202 cal BP (SUERC-68873) (150-152 cm). A further date from LF3 in core 191VC returned an age beyond the range of radiocarbon dating.

In the two cores from the inner shelf offshore of Connemara LF2 consists of alternating beds of fine sand and clay-silt with abundant single and paired bivalves as well as shell fragments. These beds are contorted and show prominent development of sub-vertical to vertical wavy laminae consistent with water escape structures, as well as localised development of ball and pillow structures (Fig. 9). The boundaries of the individual laminae are often blurred and hard to discern. In both these cores LF3 exhibits localised zones of bioturbation in the form of Chondrites burrows. The matrix is soft to firm, with shear strength measurements not exceeding 20 kPa. The physical properties collected on these cores show a low average wet bulk density of 1.98 gr/mm but a very high magnetic susceptibility averaging 271 $x10^{-5}$ SI.

4.2.4. LF4: Massive mud (Fm)

LF4 is the basal lithofacies in core 186VC only (Fig. 6) and consists of a dark grey (2.5Y 4/1) clast-free, massive silty clay (Fm) that is very compact, increasing in shear strength from 70

kPa to 150 kPa. It contains occasional silt stringers and isolated zones of diffuse stratification towards the top of this bed that are only visible in the x-radiographs. LF4 was not dated. Both the wet bulk density and magnetic susceptibility are low, averaging only 1.98 gr/mm and 85.6 $x10^{-5}$ SI respectively, and contrast with the overlying Fl (def) (FF3) where these averages are considerable higher (see Supplementary Information for more detail). This is likely a result of the change in matrix with the overlying Fl (def) containing a large sand component.

4.2.5 LF5: Matrix-supported gravel (Gms)

LF5 is a matrix-supported gravel with a muddy-sandy matrix and abundant shell fragments (Gms). This lithofacies is poorly sorted with sub-rounded to sub-angular clasts that range in size from 0.5 to 3 cm in diameter. The upper and lower boundaries range from sharp to diffuse, and where overlain by LF7 (Sm) the boundary is often gradational. LF5 occurs in all the cores from the inner shelf offshore of Connemara forming a 10-70 cm thick unit that directly overlies LF3 or LF2 and is overlain in turn by LF7. LF5 was recovered in four cores on the inner- and mid-shelf (186VC, 192VC, 193VC and 208VC, Fig. 6). In these cores, individual beds of LF5 range in thickness from 10-44 cm and often have a sharp upper and lower boundary. The exception is core 193VC where the Gms of LF5 grades into the overlying LF7. The physical properties show high average values for both wet bulk density, 2.26 gr/mm, and magnetic susceptibility, 240.3 $x10^{-5}$ SI.

4.2.6. LF6: Clast supported gravel (Gm)

LF6 is identified in three cores from the outer mid-shelf (190VC 192VC and 193VC Fig. 6). LF6 comprises massive, clast-supported gravel (Gm) with clast size ranging from 0.5-4 cm in diameter. It forms the upper lithofacies in core 192VC. In core 193VC LF6 forms two beds; the lowermost is 20 cm thick and directly overlies LF1 whilst the second is interbedded with

499 the Gms of LF5 and is only 10 cm thick. Finally, a 12 cm thick bed directly overlying LF2
500 occurs in core 190VC. As expected with a large gravel component, both the wet bulk density
501 and magnetic susceptibility are exceedingly high with average values of 2.45 gr/mm and 718.6
502 $x10^{-5}$ SI respectively.
503
504 *4.2.7. LF7: Massive sand (Sm)*
505 LF7 is the uppermost lithofacies in all cores collected in the study area, with the sole exception
506 of 192VC. LF7 is a saturated, olive (5Y 4/3), massive, bioturbated fine to medium sand (Sm)
507 containing abundant shell fragments and occasional gravel size clasts. The basal contact is
508 sharp, convoluted and often truncates, mixes with or intrudes the underlying unit. LF7 is
509 relatively thin in the slope and mid-shelf cores, ranging from 20 to 115 cm in thickness. In the
510 cores from the inner shelf, offshore Connemara, LF7 ranges from 30 cm to a maximum of 480
511 cm in core 179PC. The wet bulk density is low, averaging 1.99 gr/mm whilst the magnetic
512 susceptibility provides a medium average 124.45 $x10^{-5}$ SI. A basal radiocarbon age from a shell
513 fragment in core 179PC provides a limiting age for this unit of 12,684 ± 96 cal BP (SUERC-
514 63556).
515
516 **4.3. Lithofacies Interpretations**
517 *4.3.1. LF1: Massive diamicton (Dmm) and minor stratified diamicton (minor Dms)*
518 Massive, matrix-supported diamictons can be produced by several processes including debris
519 flows (Eyles and Eyles 1989), iceberg rafting and scouring (Dowdeswell et al., 1994;
520 Woodworth-Lynas and Dowdeswell, 1994), as well as subglacial deposition/deformation
521 (Evans, 2018). The shear strengths of this lithofacies, however, are consistently high, in some
522 cases reaching 210 kPa, implying they are overconsolidated. This is difficult to reconcile with
523 an origin as a subaqueous debris flow or iceberg-rafted deposit produced by rain out through

524 the water column. Such processes would be much more likely to produce sediments with low
525 shear strengths. Thus, the high shear strengths suggest that formation of LF1 involved sediment
526 compaction. Massive diamictons with high shear strengths from glaciated continental shelves
527 have often been interpreted as subglacial tills with the high shear strengths attributed to
528 compaction by grounded ice (Wellner et al., 2001; Dowdeswell et al., 2004; Ó Cofaigh et al.,
529 2005, 2013**).** This is our preferred interpretation for cores 193VC, 191VC, 187VC and the basal
530 160 cm of core 195VC. The deformed mud beneath LF1 in core 191VC also supports this
531 interpretation. The presence of shell fragments in LF1 implies reworking of marine fauna.
532 Dates on such reworked shells provide a maximum age for the enclosing till and thus for ice
533 advance. Based on the date of 26.4 cal ka BP from the till in 193VC from the mid-shelf
534 grounding-zone wedge (see section 4.2.1 above) this indicates that ice was grounded on the
535 mid-shelf west of Ireland after 26.4 cal ka BP.
536
537 The massive diamictons in cores 211VC and 196VC are, however, more difficult to reconcile
538 with an interpretation as subglacial till. In 211VC the youngest radiocarbon date from a
539 reworked shell indicates diamicton formation after 17.3 cal ka BP. Similarly, a reworked shell
540 in 196VC dated 15.3 cal ka BP. However, deglacial ages from the base of core 184PC from the
541 inner shelf, 103 km further inshore of 211VC indicate that that site was ice free by at least 17.1
542 cal ka BP or even earlier (see section 4.3). It is therefore unlikely that the ice sheet was still
543 grounded on the mid-shelf at this time. Taking into account both the high shear strengths of
544 LF1 in 211VC and 196VC and the radiocarbon dates, we suggest that the massive diamicton
545 in both these cores is most likely to be an iceberg turbate (cf. Woodworth-Lynas and
546 Dowdeswell, 1994) with younger material being mixed into the underlying sediment, hence
547 the young ages. Such scouring by the keels of grounded icebergs would be expected to deform
548 and compact the surrounding sediment and offers a plausible explanation for the high shear

549 strengths in LF1. This interpretation is further supported by the seismic data that shows clear
550 evidence of iceberg scouring on the bathymetric high, where core 196VC was located (Fig. 3).
551
552 In the upper 250 cm of core 195VC LF1 comprises matrix-supported diamicton that is
553 predominantly massive but in places is diffusely stratified (minor Dms). The associated shear
554 strengths are relatively low, particularly when compared to the subglacial tills described above.
555 We interpret these characteristics as compatible with a subaqueous depositional environment
556 at 22.8 cal ka BP in which sedimentation was by the rain-out of iceberg-rafted debris
557 supplemented by suspension settling from turbid meltwater plumes (Dowdeswell et al., 1994,
558 2000; Cowan et al., 1997**).**
559
560 *4.3.2. LF2: Laminated mud (Fl)*
561 Laminated clast-poor muds with abundant marine fauna, including articulated bivalves and
562 well preserved glacimarine foraminifera such as *E. clavatum* and *C. reniforme*, are indicative
563 of meltwater-related sedimentation in a glacimarine environment (Lloyd et al., 2011; Jennings
564 et al., 2017). They indicate that the core sites were free of grounded ice at the time of LF2
565 formation and thus that this lithofacies formed during ice-sheet retreat. Such laminated
566 glacimarine muds can form by a range of processes including suspension settling from turbid
567 overflow plumes (Cowan and Powell, 1990; Ó Cofaigh and Dowdeswell, 2001; Mugford and
568 Dowdeswell, 2011) or deposition from fine-grained turbidity currents (Stow and Shanmugam.,
569 1980). Laminae within 194VC are well preserved and in places have a wispy appearance with
570 laminae boundaries sometimes blurred and hard to define. We suggest that these sediments are
571 predominantly the result of suspension settling from turbid plumes (Hesse et al., 1997; Lucchi
572 et al., 2013) with a minimal contribution from iceberg rafting. A basal date of 24.4 cal ka BP

573 from LF2 in the base of core 194VC shows that glacimarine conditions prevailed at this core
574 site at that time and the site was free of grounded ice.
575
576 In contrast, the low shear strength laminated sequences from the cores on the inner shelf
577 offshore Connemara show greater variability in terms of thickness, the occasional presence of
578 load structures and clear normal grading as well as discrete granule horizons, characteristics
579 which we suggest indicates that they formed, at least in part, from turbidity currents facilitated
580 by the irregular topography of the inner shelf (Stow and Piper., 1984). The three dates from the
581 bases of cores 180PC and 184PC indicate the inner shelf was free of grounded ice by at least
582 17.1 cal ka BP.
583
584 *4.3.3. FL3: Deformed laminated mud (Fl (def))*
585 Formation of the deformed laminated muds recovered from basin fills across the mid-shelf is
586 inferred to have occurred in two-stages. The first stage involved deposition by a range of
587 subaqueous processes similar to that producing the laminated muds of LF2 (see above). These
588 muds were then deformed by an oscillating grounded ice margin. The evidence for this is
589 fivefold: (i) the presence of contortion, load structures and water escape structures (e.g.,
590 191VC, 190VC, 194VC); (ii) the facies relationship of LF2 and LF3 in which the deformed
591 muds characteristically overlie undeformed laminated sequences. In core 191VC undeformed
592 laminated muds are overlain by massive diamicton (LF1) and the transition between the two is
593 marked by an amalgamation zone of deformed mixed sediment. This facies sequence is
594 consistent with a glacitectonite-subglacial till origin in which laminated glacimarine sediments
595 are overridden by grounded ice (cf. Ó Cofaigh et al., 2011; Evans 2018). Core 194VC shows a
596 similar vertical transition from undeformed laminated mud (LF2) into heavily contorted muds;
597 (iii) high shear strengths of up to 150 kPa of the deformed facies and, in some cases the

underlying laminated muds of LF2 (e.g., core 194VC), which is consistent with compaction by grounded ice; (iv) the sequence of three ages in the deformed facies of 190VC, which are in reverse stratigraphic order; and (v) interbedding of the deformed and undeformed laminated muds in several cores (191VC and 194VC). Collectively this indicates a dynamic, oscillating grounded ice sheet on the mid-shelf that deposited and then glacitectonised glacimarine sediments during episodic retreat across the shelf. This is consistent with the study of Peters et al. (2015, 2016) who interpreted the outermost and largest grounding-zone wedge on the mid-shelf as a composite feature produced during stillstand(s) and oscillations of grounded ice.

Chronological control on the age of LF3 and the oscillatory margin is provided by several dates from cores 190VC and 194VC on the mid-shelf and mid-shelf slope respectively. The date of 24.4 cal ka BP from the base of 194VC provides a maximum age on the overriding and deformation of the laminated glacimarine sediments in this core. Similarly, in core 190VC the youngest of the three dates (23 cal ka BP) from LF3 indicates that glacimarine sediments were overridden after this time.

Deformed laminated sediments of LF4 were also recovered from the inner-shelf offshore Connemara in cores 180PC and 184PC. These sediments are characterised by low shear strength not exceeding 20 kPa and contain frequent well preserved articulated bivalves (*Yoldiella sp*.) and bioturbation. We infer that these are glacimarine sediments that, in contrast to the mid-shelf, have not been overridden by grounded ice. Rather we attribute the deformation in these sediments to relate to mass movement in which glacimarine sediments deposited on an irregular inner shelf underwent downslope resedimentation.

4.3.4. LF4: Massive mud (Fm)

Lithofacies LF4 (massive mud) was only observed in a single core (186VC). The massive, fine-grained nature of LF4 is interpreted as indicative of a quiescent glacimarine setting with sediment deposited by suspension-settling through the water column. The absence of clasts and bioturbation (burrows, mottling) suggests that iceberg delivery and/or IRD deposition and productivity were suppressed. This could be due to sedimentation in an ice-shelf cavity away from the grounding line (cf. Domack and Harris, 1988; Kilfeather et al., 2011) or the presence of sea ice fringing the ice-sheet margin (cf. Dowdeswell et al., 2000; Jennings et al., 2018). The high shear strengths that characterise this lithofacies (75-150 kPa) may reflect overriding by grounded ice similar to LF2 and LF3 above.

4.3.5. LF5, 6 and 7: Clast supported gravel (Gm), Matrix supported gravel (Gms) and Massive sand (Sm)

Massive gravel and sand units (LF5-7) form the upper lithofacies sequence in all cores collected from across the shelf. LF7 often overlies either a gravel lag or LF5 and/or LF6. This fining upward sequence of gravels (LF5), sandy gravels (LF6) to massive sands (LF7) that is seen in several cores (e.g., 193VC, 190VC, 186VC) is either evidence of a gradual weakening in bottom current activity, or alternatively represents a marine transgression and gradual increase in water depth (Vianna et al., 1998; Howe et al., 2001; Plets et al., 2015).

5. Discussion

5.1. Geomorphological and sedimentary signatures of the last British-Irish Ice Sheet on the Atlantic shelf west of Ireland

Over-consolidated subglacial tills in a series of cores (see section 4.3 above) indicate advance of the BIIS as a grounded ice mass across the continental shelf offshore of Galway Bay and western Ireland. A date on reworked shell from till in core 193VC provides a maximum age

for this advance and indicates that it occurred after 26.4 cal ka BP, and thus during the global LGM (gLGM) (26.5-19 cal ka BP; Clark et al., 2009). However, core 193VC only penetrated the upper few metres of the Mid-Shelf Grounding Zone Complex implying that much of this landform pre-dates the advance and was overridden by it. Hence, as McCarron et al. (2018) argue, the Mid-Shelf Grounding Zone Complex, may well be a product of more than one glacial cycle. The advance extended west of the Mid-Shelf Grounding Zone Complex, as indicated by the presence of subglacial till in core 195VC from the mid-shelf slope, and it grounded to at least 240 m water depth in the Slyne Trough. An extensive advance across the shelf is also supported by Peters et al. (2015, 2016) who document geomorphological and sedimentary evidence in the form of GZWs and subglacial till for grounded ice from the last glacial period further west on the Porcupine Bank. This contrasts with the interpretation of McCarron et al. (2018) who inferred the last ice sheet margin was restricted to the mid-shelf ('Irish Mainland Shelf').

Our seismic data indicate that retreat across the shelf was punctuated by stillstands and minor readvances of the grounding line. This is recorded by a series of large GZWs and intervening smaller moraines. The outermost GZW on the mid-shelf forms the large Mid-Shelf Grounding Zone Complex and is a composite, multi-crested feature, which contains overridden glacimarine muds on its eastern side implying an oscillatory grounding line. Basin fills between the GZWs across the shelf contain glacimarine sediments and are inferred to be a product of subaqueous sedimentation beyond the grounding-line when the ice sheet was positioned at a GZW. Hence, the basin fills are a product of time-transgressive deglacial glacimarine deposition. It is notable, however, that the basin fill sediments are often deformed and heavily consolidated indicating they have been overridden and glacitectonised, both on the mid-shelf and in the Slyne Trough (core site 194VC). Collectively this indicates that ice-sheet

673 retreatoccurred in a glacimarine setting and was punctuated by readvances of the grounding
674 line, which overrode and deformed these deglacial sediments (cf. Peters et al., 2016).
675
676 Although the GZWs and small moraines are both interpreted as deglacial landforms recording
677 episodic, oscillatory, grounding-line retreat across the shelf, there is a marked contrast in size
678 between them. The larger GZWs are several tens of kilometres wide and typically 10-20 m in
679 amplitude. In contrast, the moraines are less than 1 km wide with amplitudes of 5-9 m, and in
680 some cases are buried by the larger GZWs (Figs. 2, 4a, 4b, and see section 4.2 above). One
681 interpretation for the contrast in size could be that the large GZWs are associated with
682 deposition in a sub-ice shelf cavity, while the smaller ridges are a product of formation along
683 a grounded tidewater ice front (Powell and Domack, 1995; Batchelor and Dowdeswell, 2015).
684 We consider this unlikely, however, due to the intimate spatial relationship between these
685 landforms on the mid-shelf whereby the smaller moraines occur between the larger GZWs and
686 are in turn overprinted by them. A more likely explanation is that the stillstands which formed
687 the smaller buried ridges were of shorter duration than those associated with the larger GZWs
688 and/or were associated with lower sediment flux to the grounding-line.
689
690 *5.2. Timing and dynamics of ice-sheet retreat*
691 Radiocarbon dates from glacimarine sediments in our cores constrain the timing of ice sheet
692 retreat across the shelf. The earliest date on retreat is from core 194VC from the Slyne Trough.
693 Laminated glacimarine muds (LF2) from the base of the core dated 24.4 cal ka BP, showing
694 that this site was ice-free by that time (Fig. 10). It also provides a maximum age on the
695 subsequent readvance recorded in the upper part of 194VC (see section 4.3). This is
696 significantly earlier than the date of $\leq$21.8 cal ka BP proposed for initial retreat from Porcupine
697 Bank by Peters et al. (2016). Peck et al (2006) use peaks in BIIS-sourced IRD as evidence for periods

698 of ice-marginal destabilisation. They show that the first increase in BIIS-IRD occurred from 26.2-25.8
699 ka BP, but that this was followed by a more prolonged interval of high BIIS-IRD flux between 25.5-
700 23.4 which they relate to significant ice-marginal instability. This is broadly coincident with our
701 interpretation of ice-sheet retreat and ice-free conditions occurring at core site 194VC by 24.4 ka BP.
702
703 The Mid-Shelf Grounding Zone Complex marks a major grounding-line position on the mid-
704 shelf. A date of 23 cal ka BP from glacitectonised glacimarine sediments in core 190VC from
705 the east side of the moraine provides a maximum age for the most recent period of ice
706 occupancy at the moraine. The geomorphology and glacitectonised sediments reflect the
707 oscillatory grounding-line that advanced over and deformed these deglacial sediments. This is
708 broadly consistent with ice-free conditions and glacimarine sedimentation dated to 22.8 cal ka
709 BP on the slope of the Slyne Trough (core site 195VC). Additional constraint on the age of the
710 Mid-Shelf Grounding Zone Complex is provided by two dates of 21.1 cal ka BP and 18.5 cal
711 ka BP from benthic foraminifera in glacitectonised sediments from the flank of the moraine
712 (Peters et al., 2016). This indicates the grounding-line was still occupying the Mid-Shelf
713 Grounding Zone Complex at this time (Fig. 10) and deforming glacimarine sediments. Hence,
714 the Mid-Shelf Grounding Zone Complex marks a prolonged stillstand of an oscillatory
715 grounding-line on the mid-shelf. The flux of BIIS-derived IRD is variable throughout this
716 period, possibly reflecting the oscillatory pattern of ice-marginal dynamics that we record on
717 the shelf (c.f. Peck et al 2006, 2007).
718
719 The timing of ice sheet retreat and the subsequent grounding-line stabilisation at the Mid-Shelf
720 Grounding Zone Complex coincides with both Greenland Interstadial 2 (GI2; ~22-24 ka BP)
721 (Andersen et al., 2006), and the Heinrich 2 (H2) event that led to an abrupt rise in sea level at
722 c. 24 ka BP (Siddall et al., 2003; Scourse et al., 2009). The climatic and oceanographic changes
723 associated with GI2 and H2 are therefore potential external forcing mechanisms on ice sheet

dynamics on the Atlantic shelf offshore Galway Bay. However, the GZWs and smaller moraine ridges that we document across the mid-shelf point to numerous stillstands and readvances interrupting overall ice-sheet retreat. Hence, it is likely that internal mechanisms were also important controls on ice-sheet retreat dynamics. A well-known internal control on ice shelf and tidewater glacier dynamics that can act independently of climatic or oceanographic controls is sedimentation at the grounding line (Powell., 1991, Alley et al., 2007; Brinkerhoff et al., 2017). Where rates of sediment delivery to the grounding line are high, a positive feedback is introduced such that sediment deposition builds moraines or GZWs which in turn act to reduce water depth and thereby facilitate further grounding-line stabilisation and, in some cases, a short-lived readvance. Hence, while climate forcing is a plausible control on retreat dynamics across the mid-shelf given the available radiocarbon chronology, we suggest that localised internal glaciodynamic mechanisms related to sediment delivery at the grounding-line may also help to explain the numerous stillstands and the oscillatory behaviour at the Mid-Shelf Grounding-Zone Complex.

A date of 21 cal ka BP (core 211VC) from an iceberg turbate from west of the Mid-Shelf Grounding Zone Complex provides further constraint on ice-sheet retreat. It is possible that the ice sheet was still grounded at the Mid-Shelf Grounding Zone Complex at this time (Fig 10). Radiocarbon dates on deglacial sediments from offshore Connemara indicate that much of the shelf was ice-free by or before 17.1 cal ka BP (Fig. 10). There is no evidence of a significant readvance of the ice sheet onto the continental shelf after this time. Nevertheless, a date of 15.3 cal ka BP from iceberg turbate in core 196VC from west of the Mid-Shelf Grounding Zone Complex implies that icebergs were still transiting the shelf at this time, although the source of these bergs cannot be determined from the available data.

6. Conclusions

New acoustic stratigraphic, sedimentological and geochronological data from the continental shelf offshore central western Ireland provides new insights on the timing and style of ice sheet advance and retreat during the last glacial cycle. From the integrated analysis, a five-fold sequence of events is proposed below (see Fig. 10).

1. Ice sheet advance to a Mid-Shelf Grounding Zone Complex sometime after 26.4 cal ka BP. Subglacial till cored from within the Slyne Trough, at 240 m below sea-level, confirms that grounded ice extended beyond this mid-shelf position and likely grounded on the Porcupine Bank (cf. Peters et al ., 2015).
2. Ice sheet retreat was underway before 24.4 cal ka BP as indicated by radiocarbon dated glacimarine sediments in the Slyne Trough. The timing of initial retreat is earlier than previously proposed for this region (Peters et al., 2015, 2016) but is consistent with dates on retreat from the Atlantic shelf further to the north and south (Callard et al., 2018; Ó Cofaigh et al., 2019; Scourse et al., 2019). It is also consistent with evidence of destabalisation of the BIIS from 25.5 to 24.1 ka BP based on the peak IRD flux in deep-sea core MD01-2461 (Peck et al., 2006, 2007).
3. Overconsolidated glacimarine sediments and subglacial tills in cores from the Slyne Trough record grounding-line readvance sometime after 24.4 cal ka BP.
4. Ice sheet retreat across the shelf was characterised by a dynamic and oscillating grounding-line as recorded by GZWs, moraines and deformed glacimarine sediments. Dating of over-consolidated glacimarine muds collected in this study combined with the chronology from Peters et al. (2016) indicate that grounded ice was still oscillating at the Mid-Shelf Grounding Zone Complex between 23-18.5 cal ka BP.

5. Most of the continental shelf was ice free by 17.1 cal ka BP. Evidence of iceberg turbation at 15.3 ka BP implies a marine terminating margin at this time although we found no evidence on the shelf for a re-advance of ice after 17.1 ka BP.

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Figures:

Figure 1: Location map with a) Regional schematic map showing the maximum extent of the British Irish Ice Sheet during the last glacial, modified from Peters et al. (2015) with ice-marginal and Donegal Barra Fan positions previously published by Armishaw et al. (2000), Knutz et al. (2001), Benetti et al. (2010), Dunlop et al.(2010), Ó Cofaigh et al. (2012), Sacchetti et al. (2012), Thébaudeau et al. (2016) and Clark et al. (2018) and b) Galway Bay continental shelf showing the labelled core locations (red circles) and seismic profiles shown in Figs 2, and 7 (black lines labelled).

Figure 2: Seismic lines that span the mid-shelf trough to mid-shelf with a) in the north and b) in the south of the shelf.

Figure 3: a) close up of the seismic line over core sites 194VC-196VC with interpretation panel underneath, the vertical red lines mark the core location and penetration. Note the seabed artefact visible in the top right-hand side of this image b) core logs for core 196VC, 195VC and 194VC, with calibrated radiocarbon dates, shear strength measurements in kPa and lithofacies codes with colour representing the associated acoustic unit in the interpretation panel above.

Figure 4: Close-up seismic images from the northern line, with a) the seismic data and interpretation panel covering mounds 1 to 3 (M1-3) described in section 4.1, b) seismic data

and interpretation panel for cores locations 191VC and 190VC, and c) seismic data and interpretation panel for Mound 5 and core location 186VC. The vertical red lines mark the core location and penetration.

Figure 5: Close-up seismic image and interpretation panel of mounds 5 to 6 identified in the southern line and described in section 4.1. The vertical red lines mark the core location and penetration.

Figure 6: core logs for all cores collected on the mid-shelf, with calibrated radiocarbon dates, shear strength measurements in kPa and lithofacies codes with colour representing the associated acoustic unit in the interpretation panel of Figures 4 and 5.

Figure 7: Seismic lines from offshore Connemara coastline, inner-shelf, with a) a 23 km long seismic line with interpretation panel of the seismic data below, and b) close-up of the seismic data and interpretation panel for cores 184VC to 181VC. The vertical red lines on mark the core location and penetration.

Figure 8: Core logs of cores collected in the inner-shelf offshore the Connemara coast with calibrated radiocarbon dates, shear strength measurements in kPa and lithofacies codes with colour representing the associated acoustic unit in Figure 7.

Figure 9: Example core photograph and x-radiographs of the different lithofacies described in section 4.3. The white dashed lines mark stratigraphic boundaries.

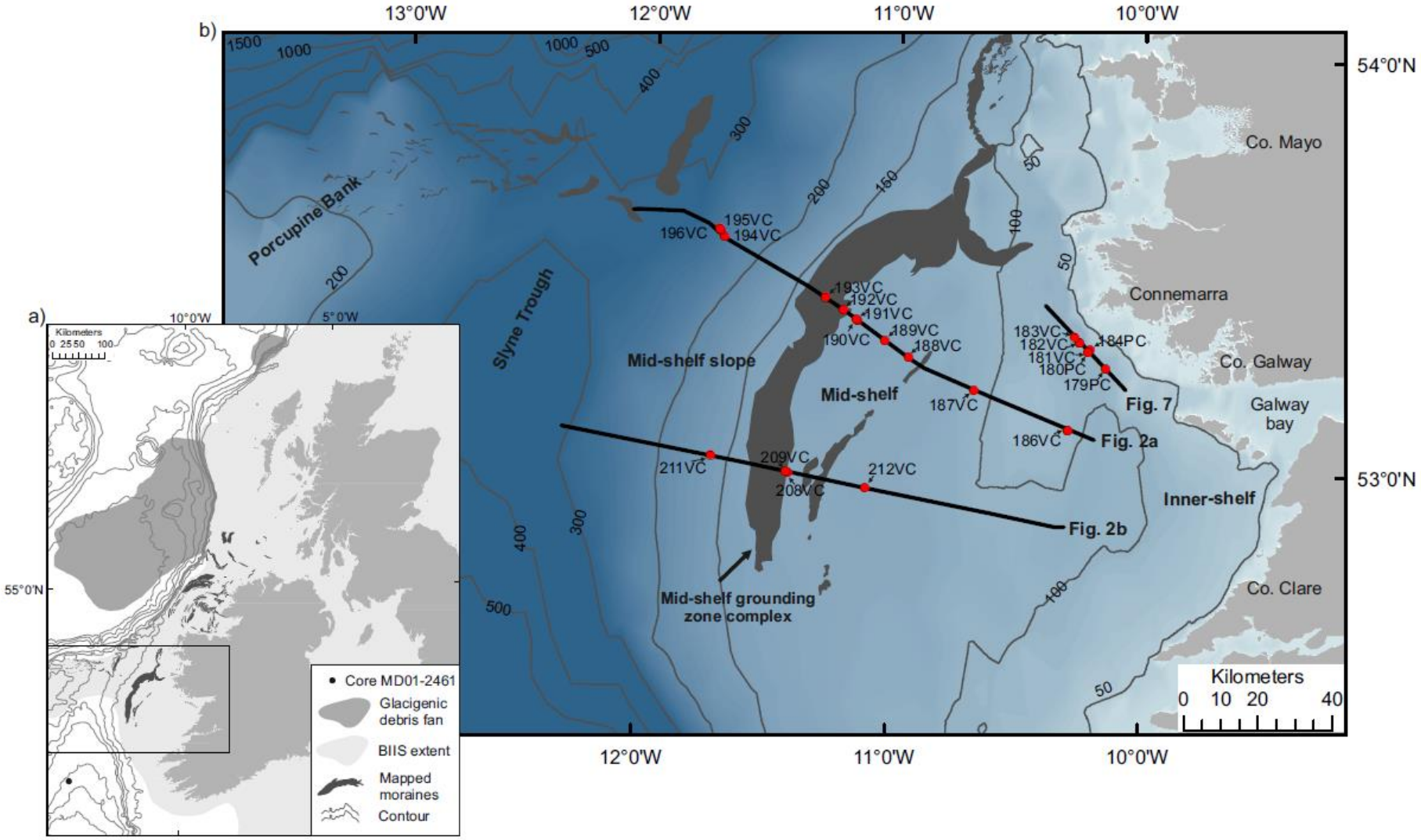
Figure 10: Time-distance diagram of ice-sheet extent on the continental shelf offshore Galway Bay from the Last Glacial Maximum (LGM) to 17 ka BP. The position of the ice sheet margin is shown as a solid black line with the dashed line representing periods of retreat. The shelf-edge position at 27-26 ka BP is implied from the IRD records of Peck at al. (2006, 2007), whilst the mid-shelf margins are based on radiocarbon dates in this study and from Peters et al. (2016). Double-ended arrows represent the oscillating ice margin on the mid-shelf

Tables

Table 1. Location, water depth and core recovery of cores collected from Galway Bay

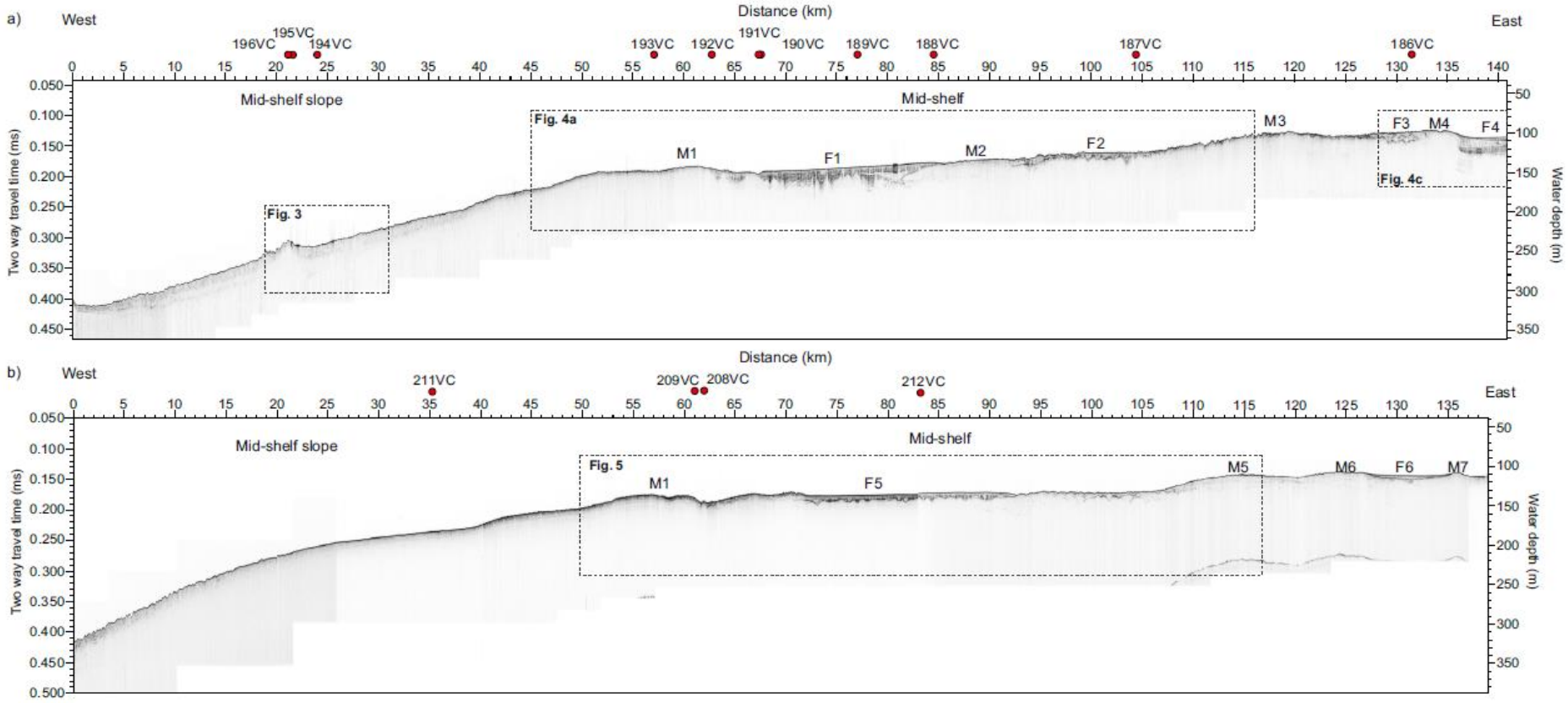
Table 2. Radiocarbon results for cores discussed in this study

1135 Figure 1

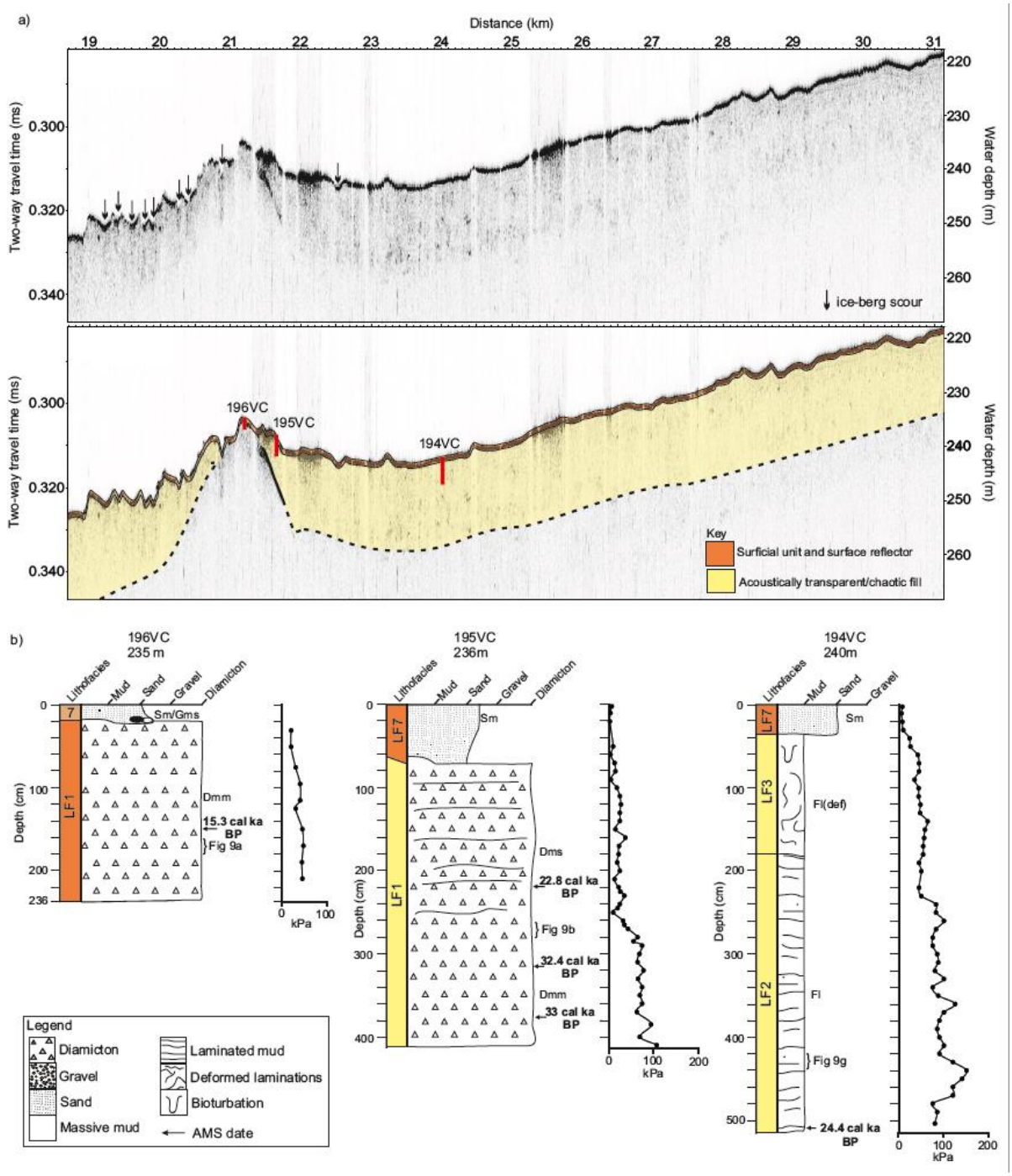


1136

Figure 2


a)
West
East
Distance (km)
196VC
195VC
194VC
193VC
192VC
191VC
190VC
189VC
188VC
187VC
186VC
Mid-shelf slope
Mid-shelf
Fig. 4a
Fig. 3
Fig. 4c
M1
F1
M2
F2
M3
F3
M4
F4
Two way travel time (ms)
Water depth (m)
b)
West
East
Distance (km)
211VC
209VC
208VC
212VC
Mid-shelf slope
Mid-shelf
Fig. 5
M1
F5
M5
M6
F6
M7
Two way travel time (ms)
Water depth (m)

1142 Figure 4



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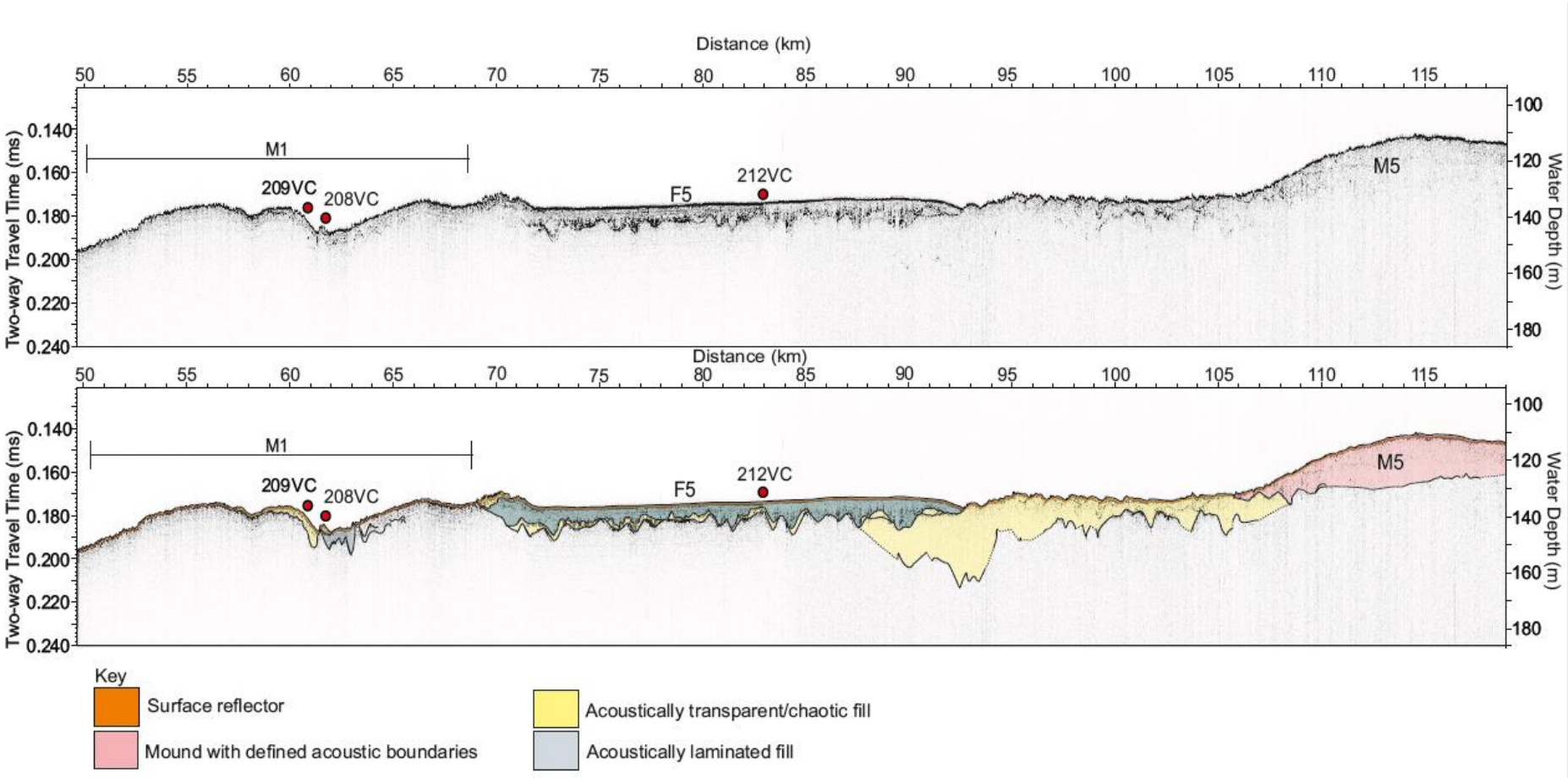
1148 Figure 5



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1151

Figure 6

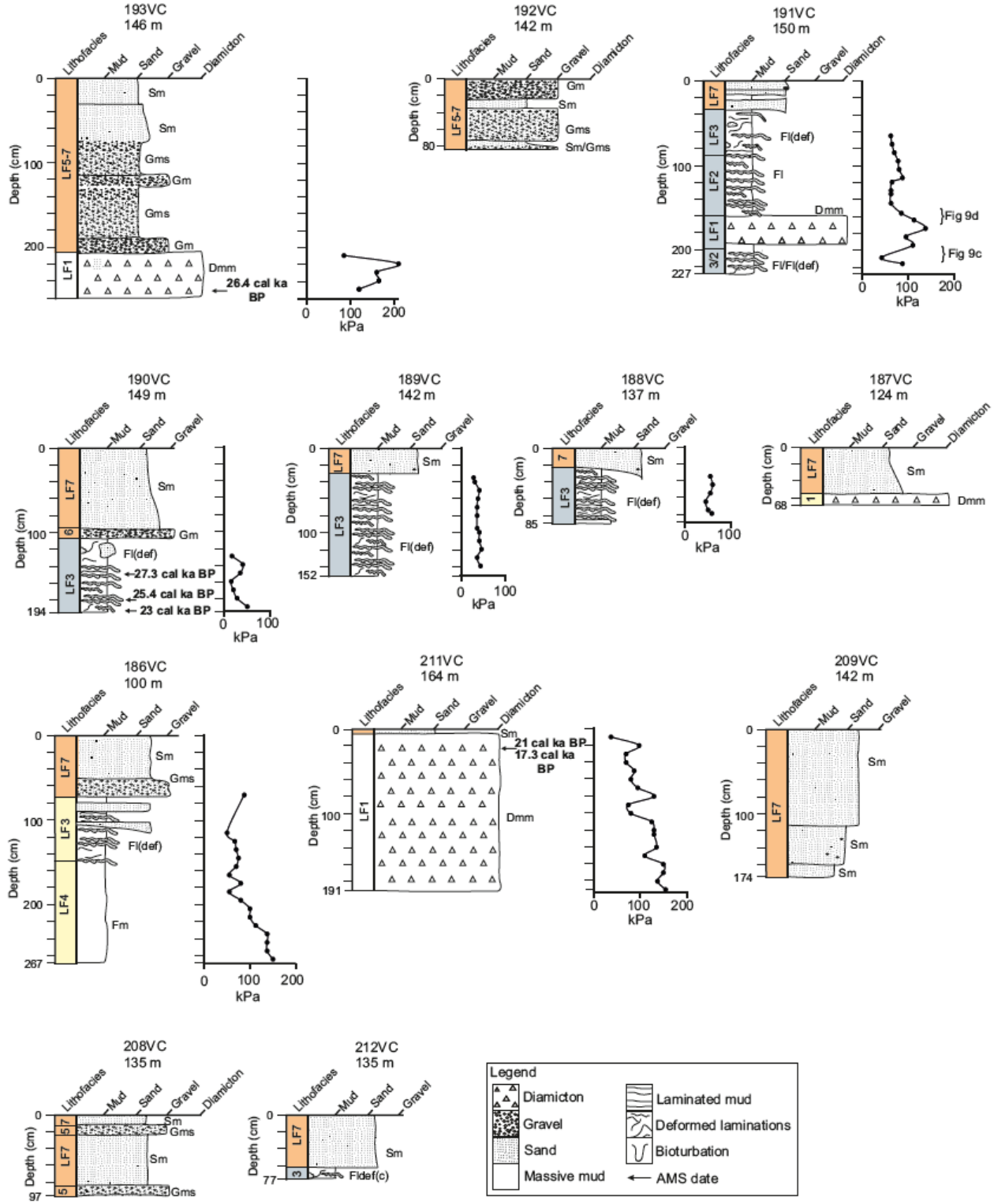

193VC
146 m
192VC
142 m
191VC
150 m
190VC
149 m
189VC
142 m
188VC
137 m
187VC
124 m
186VC
100 m
211VC
164 m
209VC
142 m
208VC
135 m
212VC
135 m
Lithofacies
Mud
Sand
Gravel
Diamicton
Depth (cm)
kPa
Sm
Gms
Gm
Dmm
Fl(def)
Fl
Fl/Fl(def)
Fm
Fldef(c)
LF1
LF2
LF3
LF4
LF5-7
LF7
26.4 cal ka BP
27.3 cal ka BP
25.4 cal ka BP
23 cal ka BP
21 cal ka BP
17.3 cal ka BP
Fig 9d
Fig 9c
Legend
Diamicton
Gravel
Sand
Massive mud
Laminated mud
Deformed laminations
Bioturbation
AMS date

Figure 7

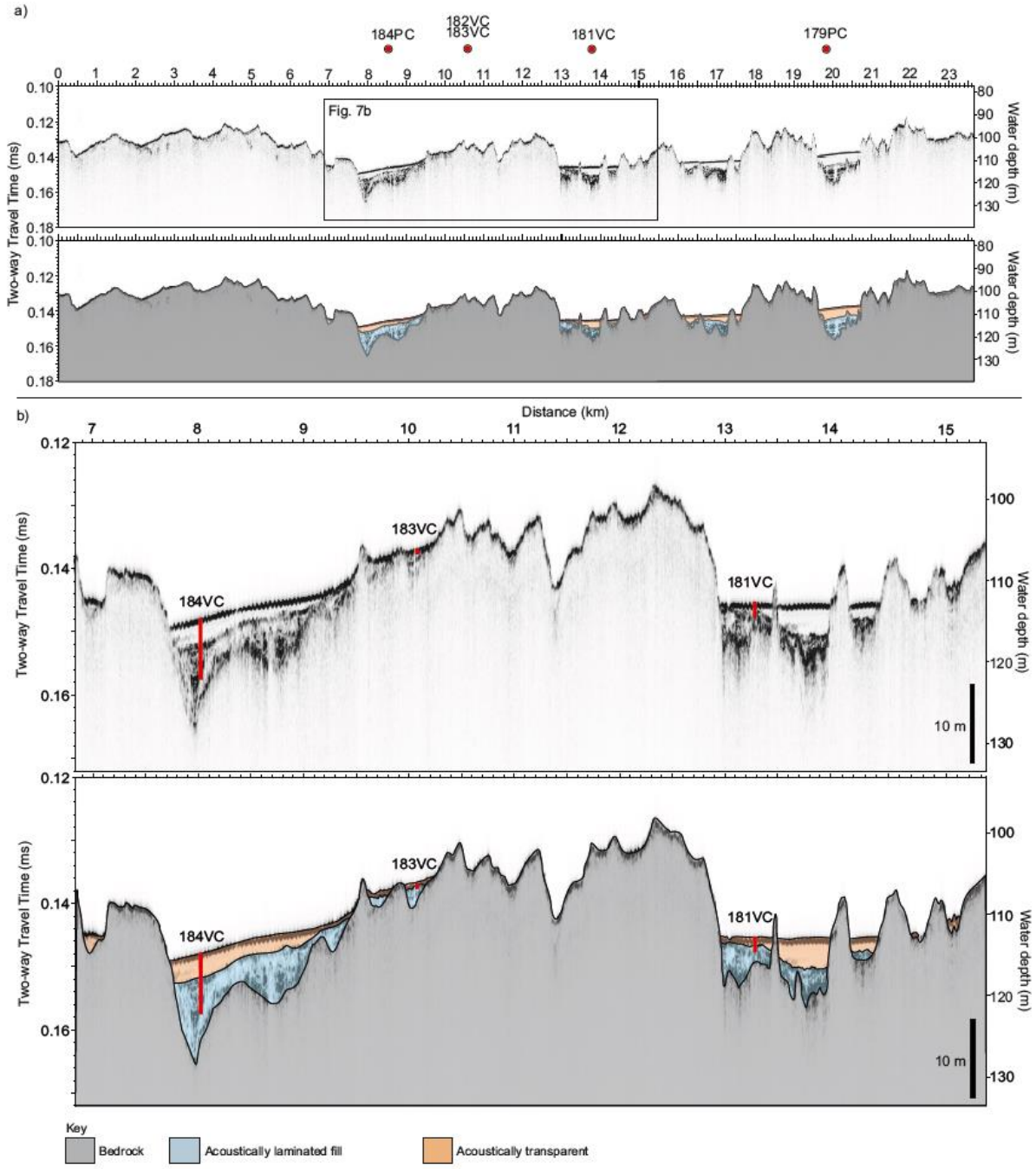

a)
184PC
182VC
183VC
181VC
179PC
Fig. 7b
Two-way Travel Time (ms)
Water depth (m)
b)
Distance (km)
184VC
183VC
181VC
10 m
Key
Bedrock
Acoustically laminated fill
Acoustically transparent

Figure 8

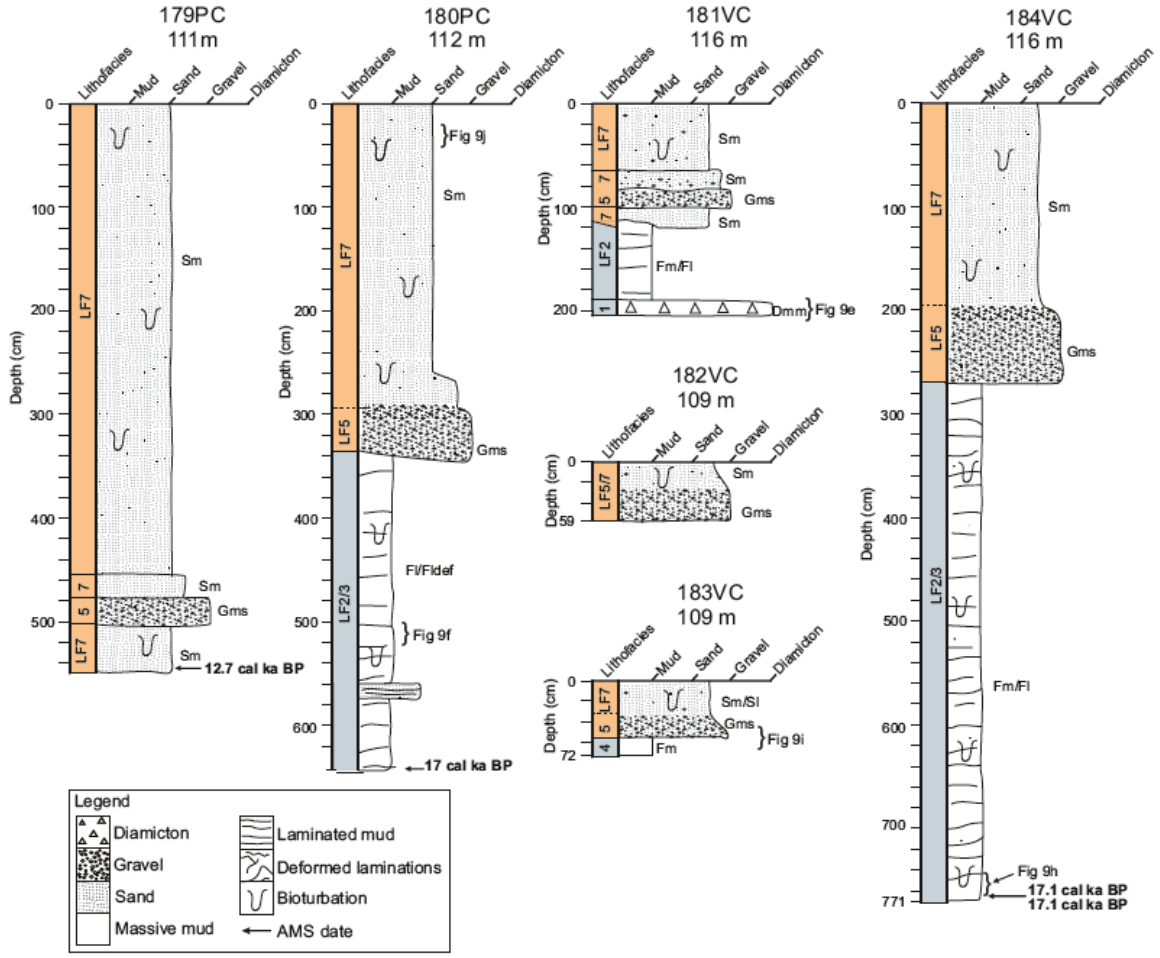

179PC
111m
180PC
112 m
181VC
116 m
182VC
109 m
183VC
109 m
184VC
116 m
Lithofacies
Mud
Sand
Gravel
Diamicton
Depth (cm)
LF7
LF5
LF2/3
LF2
LF5/7
Sm
Gms
Fm/Fl
Fl/Fldef
Dmm
Sm/Sl
Fig 9j
Fig 9f
Fig 9e
Fig 9i
Fig 9h
12.7 cal ka BP
17 cal ka BP
17.1 cal ka BP
17.1 cal ka BP
Legend
Diamicton
Gravel
Sand
Massive mud
Laminated mud
Deformed laminations
Bioturbation
AMS date

Figure 9

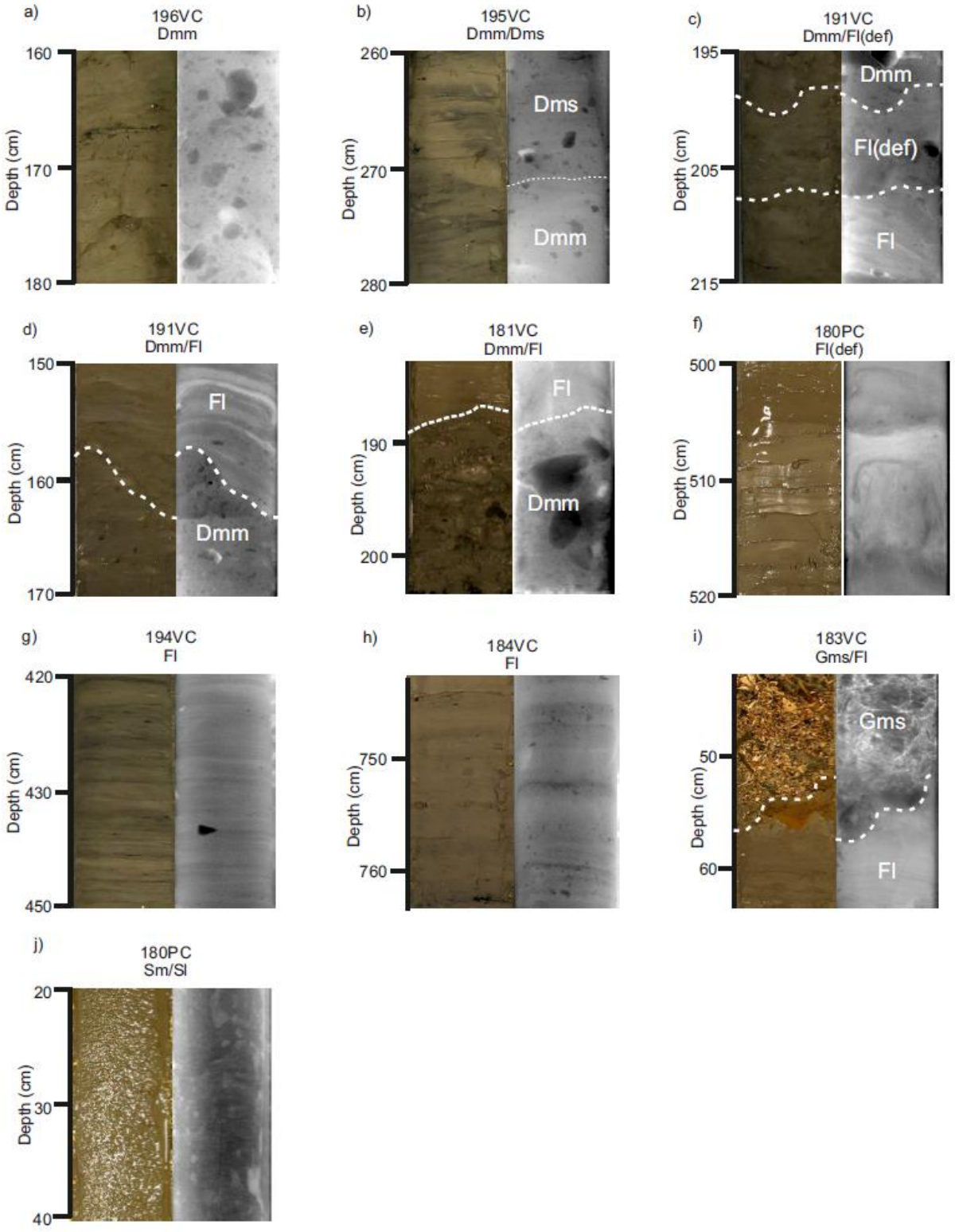
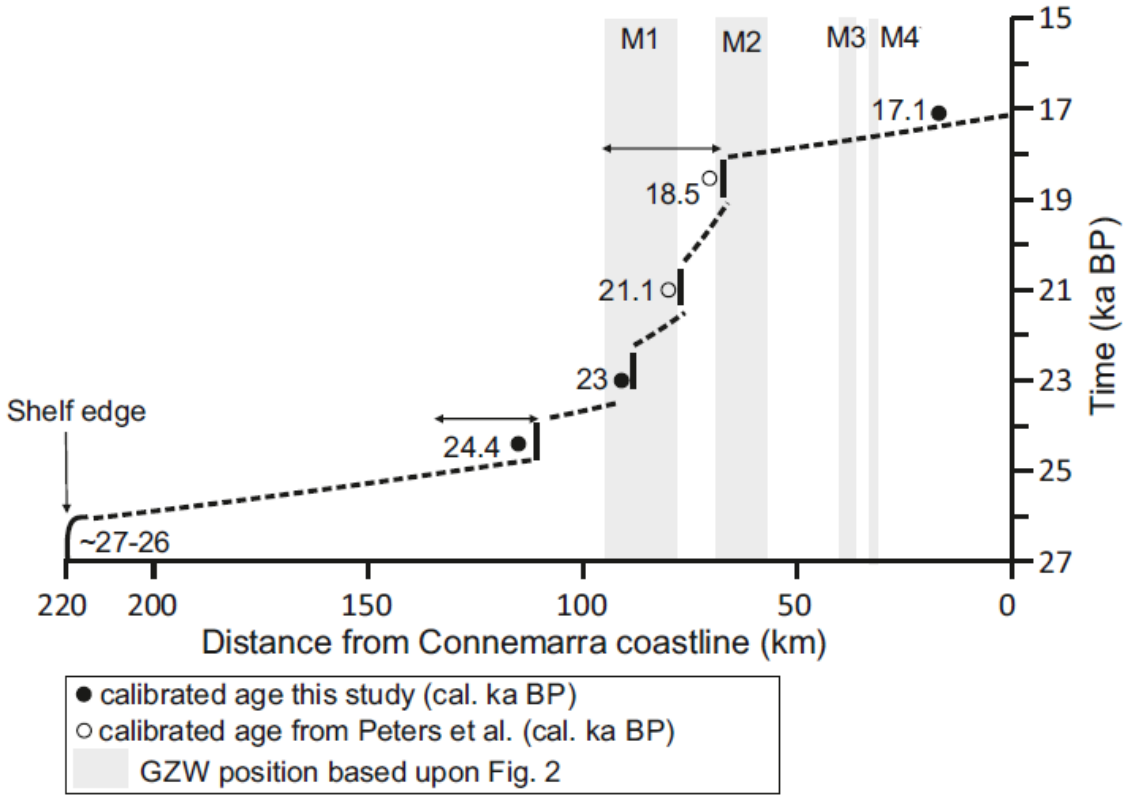
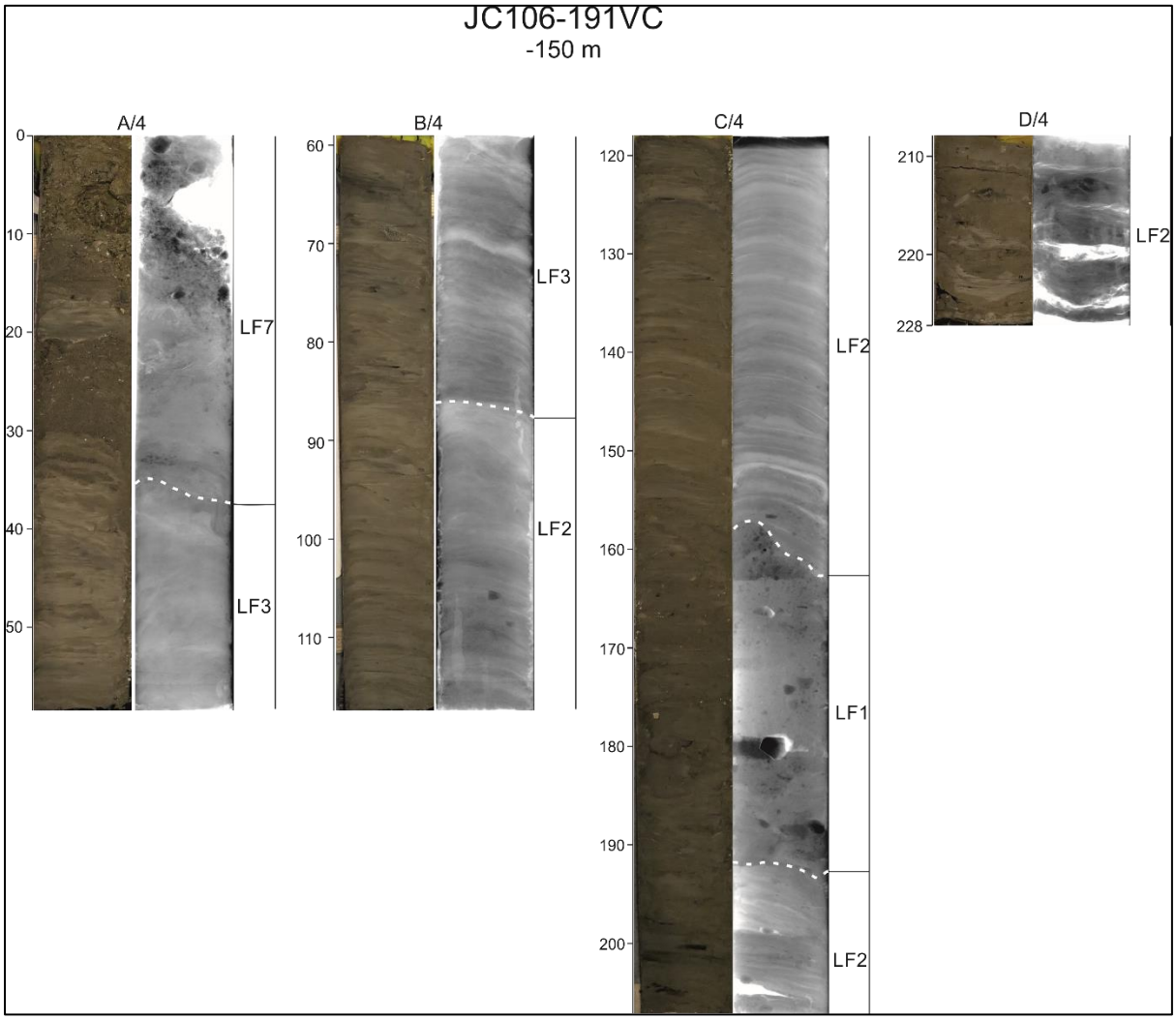

a)
196VC
Dmm
160
170
180
Depth (cm)
b)
195VC
Dmm/Dms
260
270
280
Depth (cm)
Dms
Dmm
c)
191VC
Dmm/Fl(def)
195
205
215
Depth (cm)
Dmm
Fl(def)
Fl
d)
191VC
Dmm/Fl
150
160
170
Depth (cm)
Fl
Dmm
e)
181VC
Dmm/Fl
190
200
Depth (cm)
Fl
Dmm
f)
180PC
Fl(def)
500
510
520
Depth (cm)
g)
194VC
Fl
420
430
450
Depth (cm)
h)
184VC
Fl
750
760
Depth (cm)
i)
183VC
Gms/Fl
50
60
Depth (cm)
Gms
Fl
j)
180PC
Sm/Sl
20
30
40
Depth (cm)

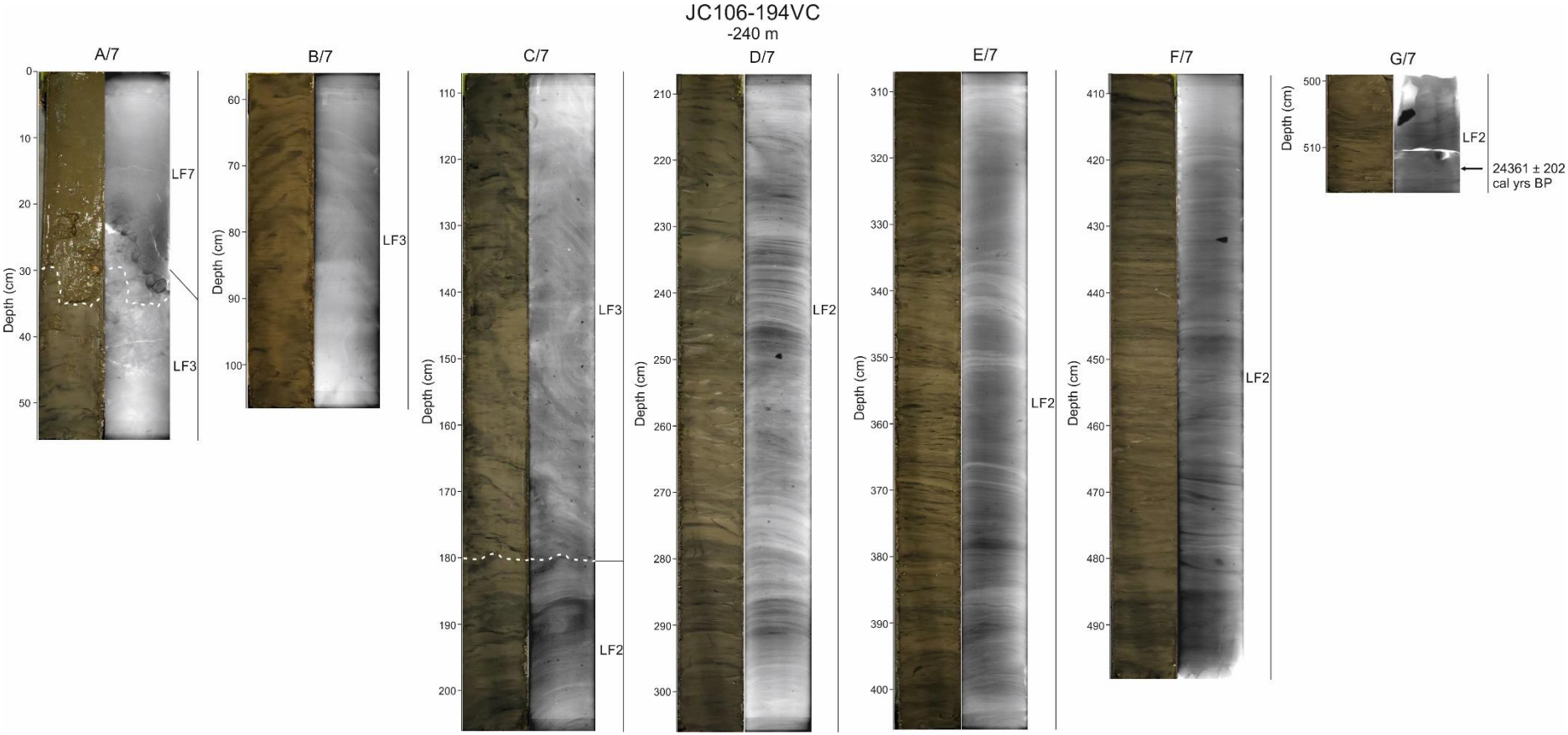
Figure 10


M1
M2
M3
M4
17.1
18.5
21.1
23
24.4
Shelf edge
~27-26
220
200
150
100
50
0
Distance from Connemarra coastline (km)
15
17
19
21
23
25
27
Time (ka BP)
calibrated age this study (cal. ka BP)
calibrated age from Peters et al. (cal. ka BP)
GZW position based upon Fig. 2

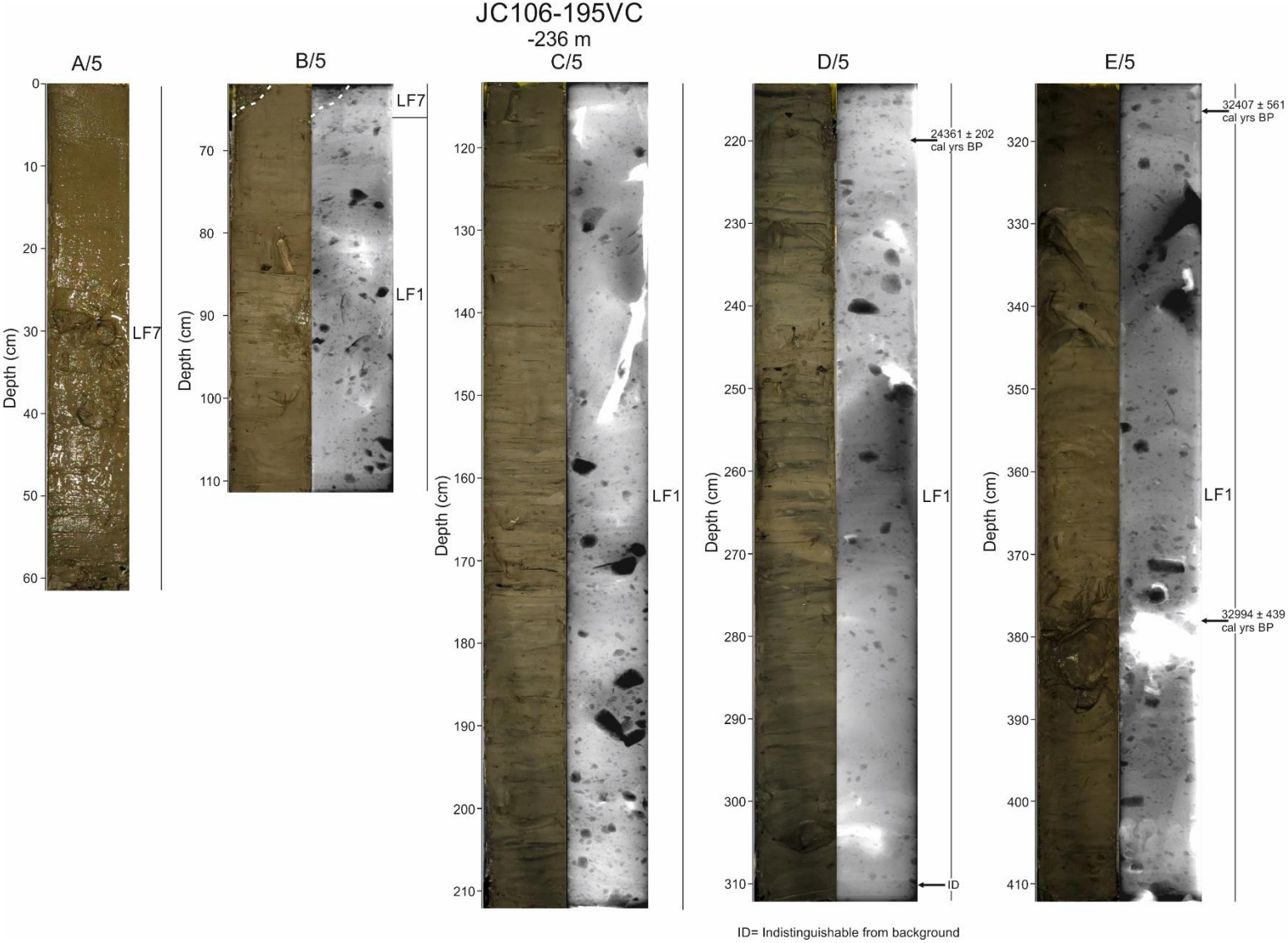
Supplementary Information



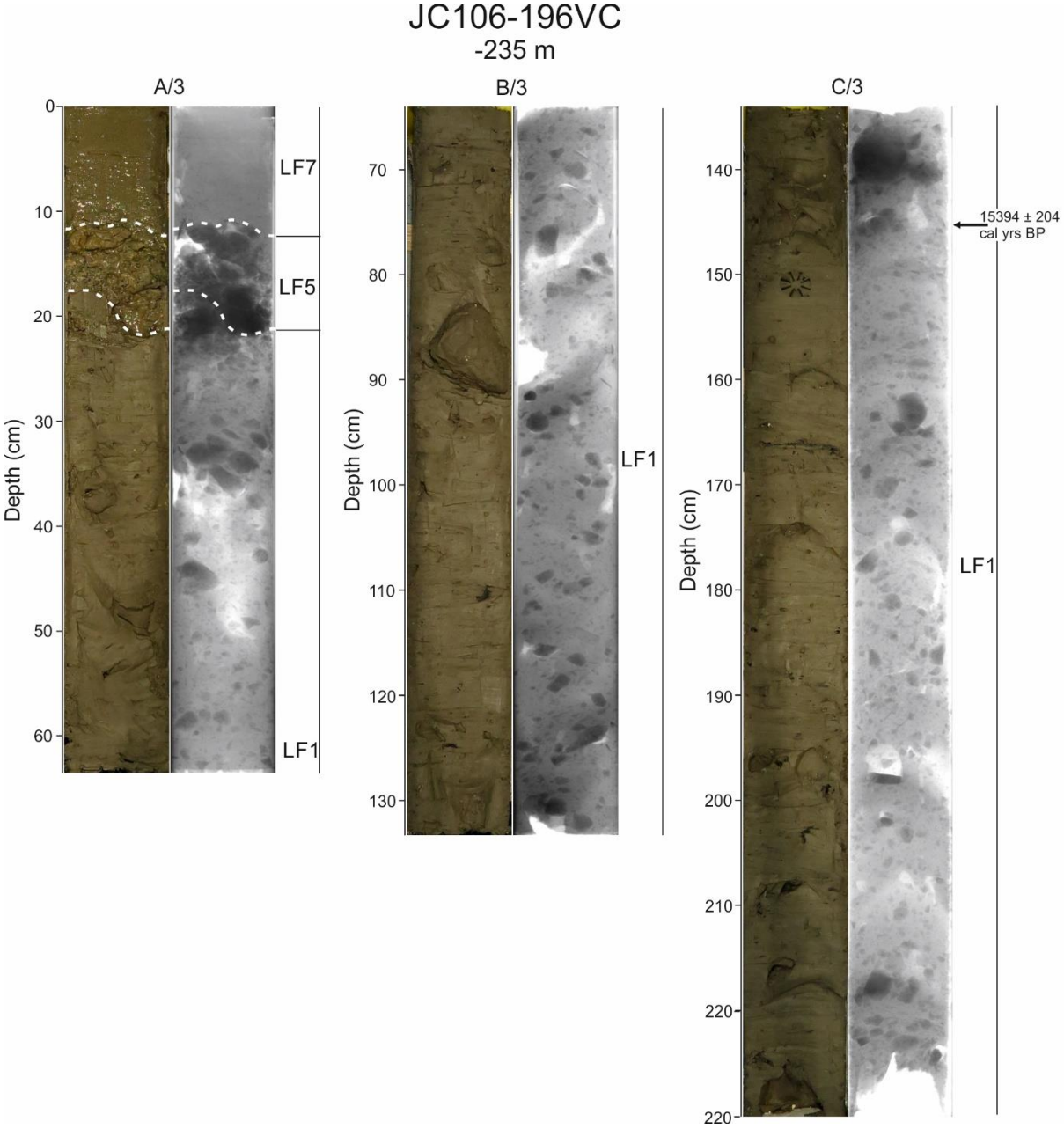
Supplementary Figure 1: X-radiograph and photograph of core 191VC with lithofacies interpretations mentioned in section 4.2 written alongside.



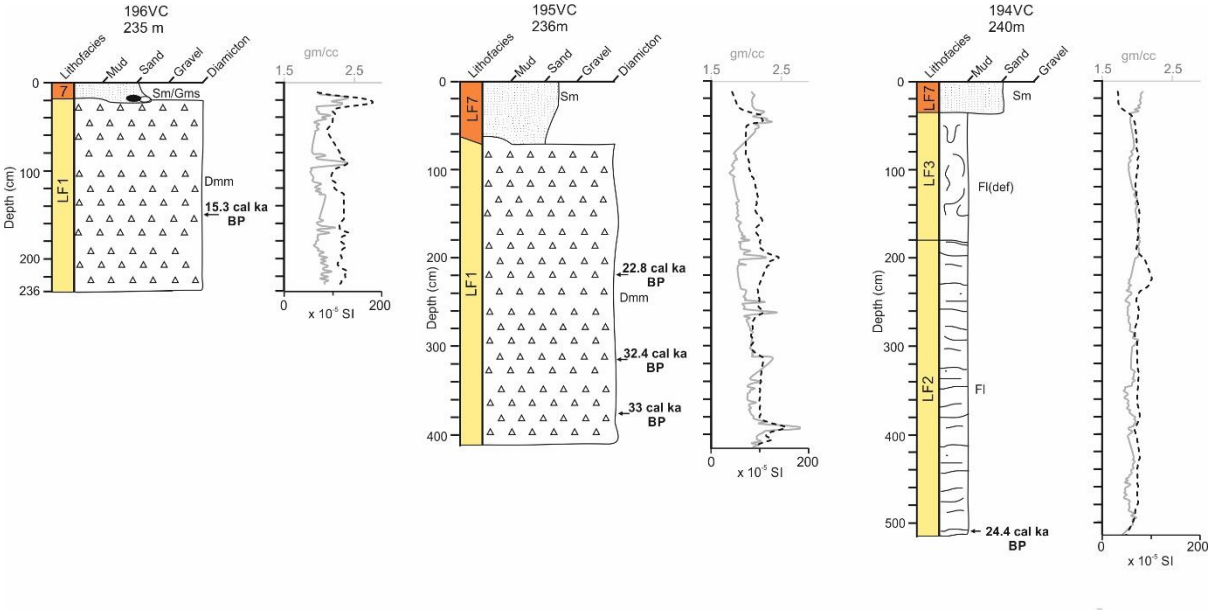
Supplementary Figure 2: X-radiograph and photograph of core 194VC with core lithofacies mentioned in section 4.2 written alongside.



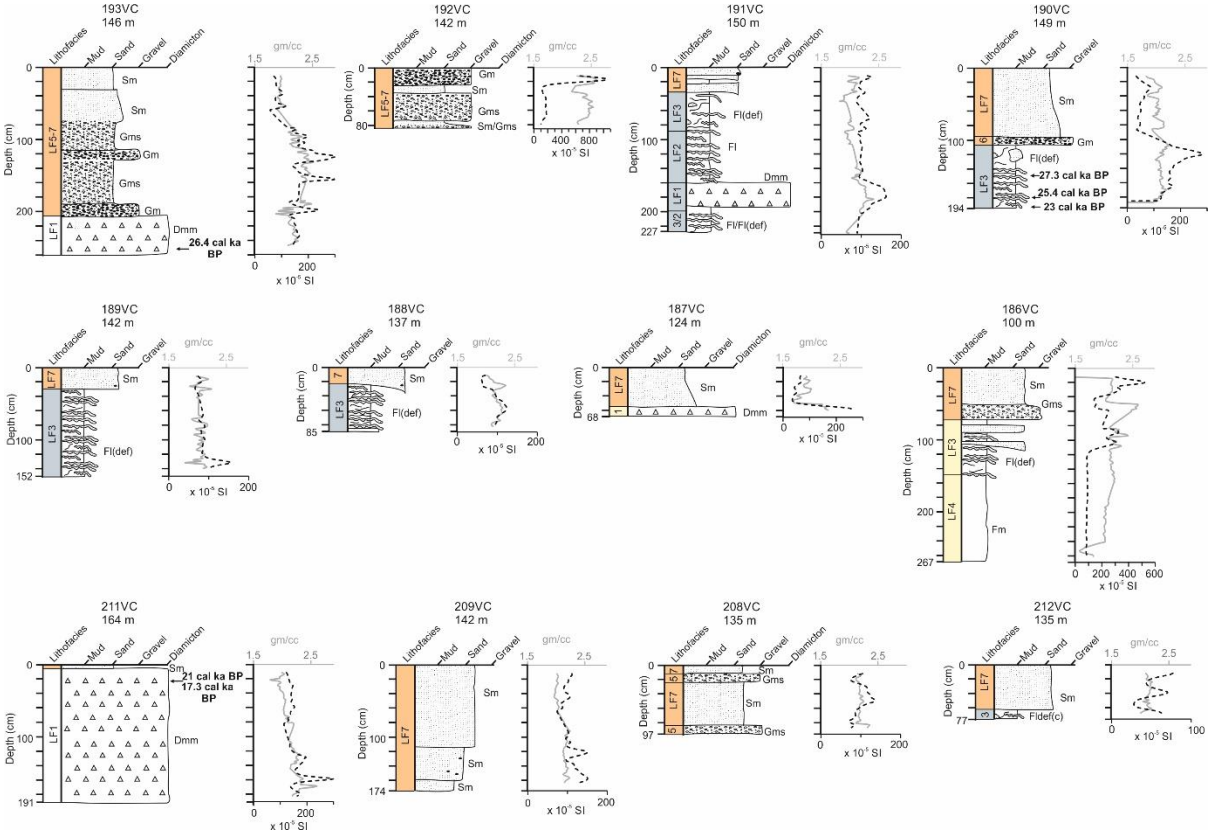
Supplementary Figure 3: X-radiograph and photograph of core 195VC with lithofacies interpretations mentioned in section 4.2 written alongside.



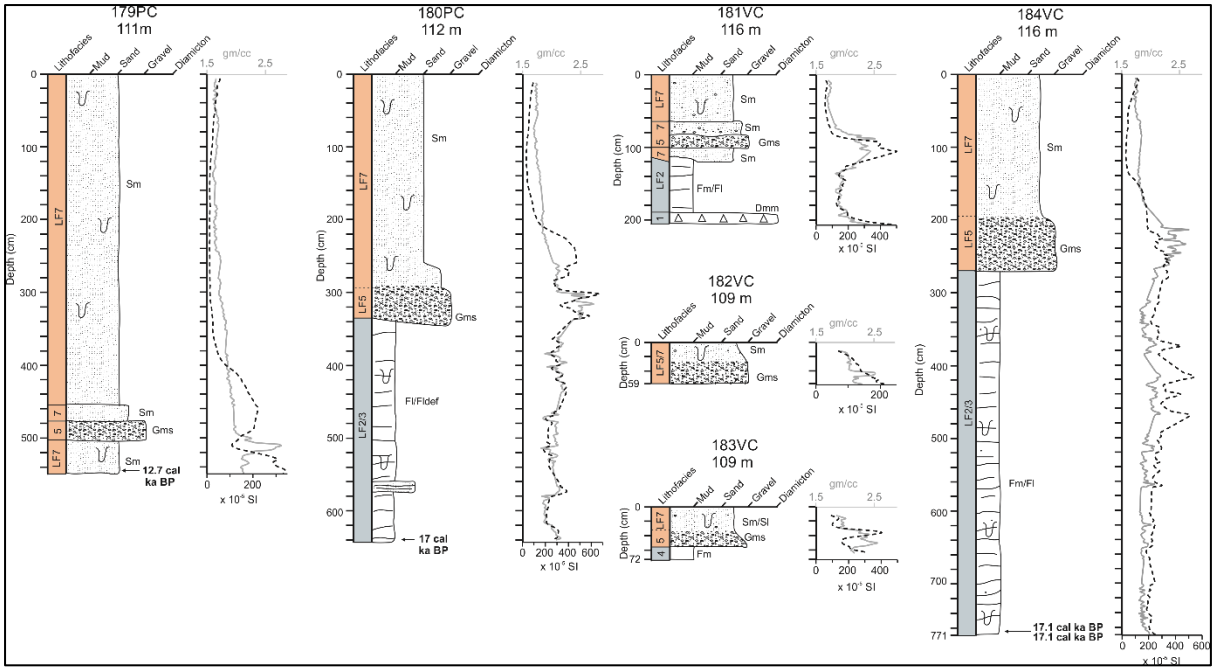
Supplementary Figure 4: X-radiograph and photograph of core 196VC with lithofacies interpretations mentioned in section 4.2 written alongside.



Supplementary Figure 5: Core logs for core 196VC, 195VC and 194VC, with calibrated radiocarbon dates and lithofacies codes with colour representing the associated acoustic unit shown in Figure 3a. The graph alongside the core logs present the wet bulk densities results (solid grey line) and magnetic susceptibility results (black dashed line).



Supplementary Figure 6: Core logs for all cores collected on the mid-shelf, with calibrated radiocarbon dates, and lithofacies codes with colour representing the associated acoustic unit in the interpretation panel of Figures 4 and 5. The graph alongside the core logs present the wet bulk densities results (solid grey line) and magnetic susceptibility results (black dashed line). Note the magnetic susceptibility scale changes between cores.



Supplementary Figure 7: Core logs of cores collected in the inner-shelf offshore the Connemara coast with calibrated radiocarbon dates, and lithofacies codes with colour representing the associated acoustic unit in Figure 7. The graph alongside the core logs present the wet bulk densities results (solid grey line) and magnetic susceptibility results (black dashed line). Note the magnetic susceptibility scale changes between cores.

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